PROCEEDINGS

OF THE

ROYAL SOCIETY OF VICTORIA

VOLUME 90

INCLUDING THE SYMPOSIUM ON
THE MURRAY-DARLING RIVER SYSTEM

ROYAL SOCIETY'S HALL
9 VICTORIA STREET, MELBOURNE 3000

Contents of Volume 90 Part 1

THE MURRAY-DARLING RIVER SYSTEM SYMPOSIUM

Papers accepted for publication by the Society and edited under the authority of the Council. The authors of the several papers are individually responsible for the accuracy of the statements made and the soundness of the opinions given therein.

Contents of Volume 90 Part 2

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In the Murray-Darling Basin, December 1860: the junction of Pamamaroo Creek with the Darling River.

This was about 7 miles upstream from the settlement at Menindee, and in October of that year Burke made his camp (No. 32) on the spit of land, centre. Then, with seven others, he immediately went forward to Cooper's Creek, leaving the balance of his party to stay at Menindee until the end of January, 1861.

The artist and naturalist with the Expedition, Ludwig Becker, was amongst those left behind, and during the three-month interval collected specimens, sketched and painted. This picture, in watercolour, was one of his paintings.

Becker died at Torowoto on the way towards Cooper's Creek in April 1861. The painting, in colour, was published in Volume 73 (the Centenary Volume) of the Society's Proceedings, 1961, by courtesy of the Trustees of the Public Library.

SYMPOSIUM ON

THE MURRAY-DARLING RIVER SYSTEM

13 OCTOBER, 1977

FOREWORD

This is the largest volume that the Royal Society of Victoria has produced and it reflects the great interest in the Symposium, The Murray-Darling River System, held in Melbourne at the Society's Hall on 13 October, 1977. The quantity of Symposium manuscripts plus some additional scientific papers accounts not only for the size of the volume but also for some delay in its appearance, for which the Publications Committee apologizes.

The Rivers Murray and Darling together have an immediate ecological and economic impact on a wide region of eastern Australia and contributors from four States have offered a diversity of papers related to their physical and biological aspects.

The Society's interest in the area is of long standing. It was from Melbourne in 1860 that the Burke and Wills Expedition set out, to move north over the Murray and establish a base camp at Menindee on the Darling. The Expedition, destined to end so tragically, was sponsored by the Exploration Committee of the Royal Society of Victoria.

Its instructions to the scientific observers attached to the Expedition, surveyor, astronomer, meteorologist, geologist, mineralogist, zoologist and botanist were explicit and designed to furnish information about the land traversed . . . "Quality of water, if any. Character of the banks and beds of streams and lakes, and of the intervening and adjacent country." At that time the extent and nature of the Murray-Darling River System was almost unknown.

The papers in this Symposium document some of the modern advances of knowledge about the area, and the Society hopes that this record will provide sources of reference as well as heuristic impulse for further advances in the future.

J. W. WARREN
Hon. Editor

1

THE MURRAY-DARLING RIVER SYSTEM

By EDMUND D. GILL*

ABSTRACT: The Murray-Darling river system is a product of the continent over which it flows, and so has remarkably low declivities (once the Dividing Range is left) and low water volumes although subject to heavy floods. Clay-rich substrates ensure the continuation of river flow over great distances in spite of low water volumes and high evaporation. These characteristics of the river course control the nature of the biota. The Pleistocene Murray extended 180 km further (across the continental shelf), and considerably increased its potential energy by debouching about 200 m lower.

INTRODUCTION

Derivationally, a river is a *divider*, viz. that which *rives*, and the people on each side are *rivals*. But from a scientific point of view, a river is a *process*, viz. water flowing across a terrain. Still water is not a river, but a lake or billabong. The nature of the process is determined by four factors: (1) The volume and energy of the water, (2) the nature of the water, (3) the substrate, and (4) the subaerial environment.

MURRAY-DARLING WATERS

Australia is the only mid-plate continent, so its tectonics are subdued, and it is the flattest continent. Because Australia lacks high mountains, is extensive, and lies in the dry latitudes, it is not only the flattest but also the driest continent. These two attributes result in the Murray-Darling being a most unusual river system. The natural Murray is of course different from the present controlled stream. For example, in 1945 I walked dry shod across the bed of the Murray near Koondrook, but controls now prevent the river from going dry.

The Murray and Darling Rivers both rise in the so-called Great Dividing Range, but have quite different hydrologic and time parameters. The Darling results from the tropical/subtropical rainfall on the Divide. It is essentially monsoon water that falls in summer. By contrast, the Murray results from temperate zone rainfall. Its water is from winter rain and spring thaw. King floods occur below the confluence of these two rivers when their floods happen to coincide. The Murray/Darling catchment is about one seventh of the continent, but the volume of water carried is small because most of the course across the plains is through semi-arid country. The Mississippi carries 20 times as much water and the Amazon 75 times.

MURRAY-DARLING RIVER COURSES (Pl. 1)

On leaving the mountains, the rivers traverse wide plains of semi-arid country. If the Darling flowed into sandy country like that of northwest Victoria, it would never meet the Murray. Substrate is here a significant factor. Widespread lateritization and bauxitization of the terrain has produced non-swelling clays, while the basalts of the Divide have produced montmorillonite. Clay-lined channels prevent loss of water by seepage. So the Darling is not lost in a sandy desert; it has many of the properties of a canal. It is the Nile of Australia. Downstream from Albury, the Murray runs through semi-arid country, where extensive clayey deposits such as the Blanchetown Clay have a profound effect on the nature of the system.

Growing curious about the course of the Murray River west of Mildura, I studied why it should run the course it does, when in such flat country so many other possibilities appear to be present. And why is the north bank commonly cliffed, but not the south? I discovered that the river follows essentially the boundary between the clayey country to the north and the sandy country to the south. For example, on the north side farmers conserve water in *tanks* which are shallow basins cut in Blanchetown Clay or such clayey sediments. On the south side the farmers dig *waterholes* which are in sand and have to be lined with clay. Once a year the channels to the waterholes are cleared, and they are filled with water from Lake Cullulleraine (for

*CSIRO Division of Applied Geomechanics, P.O. Box 54, Mt. Waverley, Victoria, Australia. 3149.

example), but about 90% of the water is lost through the sandy channels. However, the aquifers are so charged.

Because of the flow of rivers over dry flat country, and so few tributaries once the mountains and foothills are left behind, and because of the high evaporation rate (up to 2 m p.a.), the water volume of the Murray-Darling System is far below average. In those dry areas, water becomes the most precious of minerals.

MURRAY-DARLING SEDIMENTS

Clayey aquicludes play an important part in the organization of the river system and its hydrology. But what of the aquifers? The water table in the proposed Chowilla Dam area is 60 m from the surface. Because of the low declivity of the terrains, coarse sediments remain in the upper reaches of the rivers, and fine sediments characterize the Murray Basin deposits. On the Darling River between the Queensland border and the confluence with the Murray the energy levels are low and the sediments fine. The river length is x 3 the direct distance (*c.* 2,100 km) with an average fall of only 5-6 cm/km (3½″/mile). As the evaporation is *c.* 2 m/yr, carbonates load the terrain — calcite, gypsum, dolomite and barite. The river is characterized by the fineness of its sediments. An interesting example of the fineness of the sediments is that the 14 km long lunette on the east side of Lake Victoria does not consist of the usual medium sand, but of fine sand, because only fine sand is available. Because the sand is so light, it was almost always in a state of blowout during the construction of the lunette, so that there are more windblown horizontal beds than the usual 22°/33° dune structures, although these also are present.

The fineness of the sediments also influences the hydrology in that the fine sands hold more water than coarse ones. The biology is profoundly affected by this system of low energies and fine sediments. Extensive weed-growing areas exist with fish and other forms of life capable of withstanding the muddy waters and low oxygen status. For this reason introduced fish such as the European carp and redfin have done well, and trout are limited to the higher reaches of these rivers. The biota has to be able to exist in an ecosystem that consists at one time (under natural conditions) of a string of ponds, while at another it consists of a great flood up to 100 km wide.

The mild tectonics of this region result in a broad inland plain with but little relief, so flat indeed that any movement that does occur has effects quite out of proportion with its size. For example, the Cadell

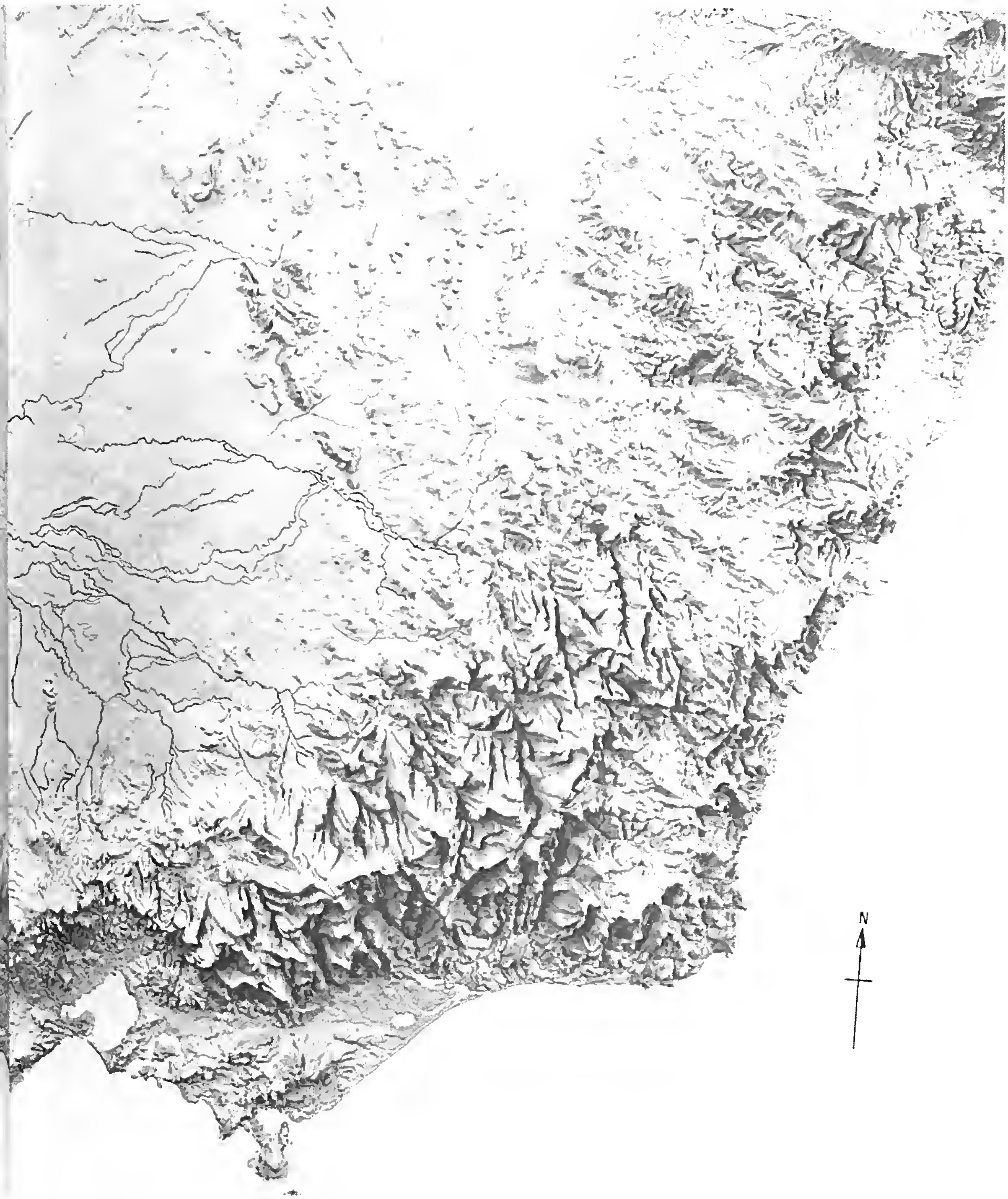

PLATE 1

Photograph by J. Walsh (CSIRO Division of Applied Geomechanics) of a model(by Professor E. S. Hills)of southeast Australia, showing the flat subquadrate Murray Basin surrounded by a frame of ancient sedimentary and plutonic rocks. The Darling River is shown flowing south to meet the Murray River, whose origin is in the Eastern Highlands.

Fault at Echuca, with a maximum throw of 12 m, diverted the Murray River south along the fault line to betrunk the Goulburn River, taking over some 80 km of its course. Some water forms an anabranch to the north. So this minor fault strongly diverted Australia's largest river, and created the Echuca Depression in which a lake was formed, and from the sandy beaches of which the Bama Sandhills were built. Because of the gentle tectonics, old faults and lineaments have not been destroyed in an upheaved crust, but slow movements have continued on them for hundreds of millions of years. Thus the faults in the Pre-Cambrian basement have for the past 120 m.y. influenced the Murray Basin in spite of 1,000 m of cover in places. Small movements still occur on these very ancient faults with remarkable effects because of the flatness of the terrain, e.g. the formation of Lake Victoria.

So the ecosystem of Australia's largest river system is a most remarkable one, and merits much more study. There is a fascinating interdependence between all the elements that make up this ecosystem — the geology, geomorphology, climate, hydrology and biology. This Symposium was organized in the hope of achieving a greater integration of the vast amount of information available.

MURRAY DEBOUCHEMENT

The Darling River debouches into the Murray River at Wentworth, but with a twin stream, the Darling Anabranch. Wentworth is about 820 km by river from the sea, but only a little over 30 m above sea level. At Murray Bridge the granite bars below the river sediments are 40 m below sea level, the bed having been cut low during times of low sea level. Before entering the sea the river debouches into Lake Alexandria which is practically horizontal (declivity of 1″/mile, say 1 cm/km). This lake is a creation of the Flandrian Transgression. From the Murray mouth to the edge of the continental shelf is 180 km, a declivity of 1 in 900. There are submarine canyons on the edge of the continental shelf, and these are commonly regarded as old mouths of the Murray. Certainly when sea level was low, the course of the Murray was much longer, and the lower part at least of its system would be rejuvenated by the provision of a lower base level.

HISTORY OF THE MURRAY-DARLING SYSTEM

The drainage of this area was first provided for by two great events: the retreat of the Cretaceous epeiric seas, which provided a terrain, and the separation of Antarctica and Australia, which provided a coast onto which rivers could flow. Changing world climates, and the changing position of the Australian continent as it drifted north have been major influences. Much of the story is unknown, but the Tertiary sea did invade the Murray Basin, in the Miocene reaching as far as Deniliquin, thus strongly betrunking the rivers. Some think that the Darling did not break through the Cobar Gap until the Pliocene. Certainly in the Miocene the climate was subtropical with high rainfall and forests including *Araucaria* and *Agathis* as far south as Victoria, where large crocodilians were also to be found. In the Pliocene laterites were formed, indicating a monsoon type climate. Then the forests disappeared and sclerophyll plants came to dominate the region, and carbonates instead of iron came to dominate the surface chemistry.

After the sea retreated from the Murray Basin, the Pinnaroo Block was uplifted in the South Australian sector, so that a great freshwater lake or series of lakes formed inland called Lake Bungunnia. For the present, it is something of a mystery how and when the present lower Murray course as we know it became established. But it has cut a course through this block, forming the Murray Gorge, along the walls of which can be seen the Miocene and Pliocene sediments laid down by the marine transgression. So the Murray-Darling ecosystem is one that reaches far into a past with great changes in the nature of the environment. This is a history that we are only beginning to unravel.


GEOMORPHIC MAP
MALLEE REGION
NORTHERN VICTORIA AND
WESTERN NEW SOUTH WALES
0 10 20 30 40 50
kilometres
LOW LEVEL ALLUVIUM
HIGH LEVEL ALLUVIUM
CLAY PLAIN
CLAY PLAIN WITH SAND COVER
LACUSTRINE
LAKE FLOOR
GYPSEOUS LAKE FLOOR OR PLAIN
AEOLIAN
SAND PLAIN
LINEAR DUNES
IRREGULAR SUB-PARABOLIC DUNES
LUNETTES
BEDROCK HILLS
NORTH SOUTH RIDGES –
POSSIBLE TERTIARY STRANDLINES
142°
143°
144°
33°
34°
35°
36°
PAMAMAROO LAKE
MENINDEE LAKE
MENINDEE
Talyawalka
Darling River
CAWNDILLA LAKE
EUCALYPTUS L.
RATCATCHERS LAKE
VICTORIA L.
BOOLABOOLKA
MANARA HILLS
TANDOU LAKE
Tandou Creek
Redbank Creek
DARNICK RANGE
MOORANYAH
Creek
POPILTA L.
POPIO L.
MINDONA L.
MANFRED RANGE
LAKE MULURULU
Willandra
TRAVELLERS LAKE
NIALIA L.
YELTOW
NEARIE L.
NITCHIE L.
WARRAWENIA L.
MILKENGAY
POONCARIE
LAKE GARNPUNG
LAKE LEAGHUR
LAKE MUNGO
OUTER ARUMPO L.
Anabranch
River
HATFIELD
TYSON L.
LAKE VICTORIA
MURRAY RIVER
Darling
WENTWORTH
GOL GOL
MILDURA
Willandra
PRUNGLE LAKES
Creek
PITARPUNGA
River
LAKE BENANEE
ROBINVALE
BALRANALD
Murrumbidgee
RAAK PLAIN
HATTAH LAKES
SUNSET DESERT
Wakool
Edward
River
OUYEN
MANANGATANG
MURRAYVILLE
LAKE TYRRELL
L. TIMBORAM
GREEN WHAPOOL
SWAN HILL
LAKE BOGA
MURRAY
SEA LAKE
LAKE TUTCHEWOP
KANGAROO LAKE
RIVER
Loddon
BIG DESERT
Outlet Creek
Lalbert Creek
Tyrrell Creek
Avoca River
L. ALBACUTYA
KERANG
RAINBOW
Yarriambiack Creek
BIRCHIP
L. HINDMARSH
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2

GEOMORPHOLOGY OF THE MALLEE REGION IN SEMI-ARID NORTHERN VICTORIA AND WESTERN NEW SOUTH WALES

By J. M. BOWLER* AND J. W. MAGEE*

ABSTRACT: A geomorphic map of the Mallee Region displays a variety of landforms characteristic of semi-arid southeastern Australia. Landform units have been identified primarily on a basis of the fluvial, lacustrine and aeolian processes that controlled them. Sand dunes constructed by prevailing westerly winds have extended from west to east in an area that includes the tributary junctions of the Murray-Darling system. Interference between aeolian and fluvial processes has combined to produce a complex network of terminal and groundwater lake basins which preserve the legacy of past changes in the hydrologic regime.

The construction of linear and irregular to sub-parabolic sand dunes and transverse clay-rich lunettes, previously dated as coinciding with the glacial maximum, is related to periods of major hydrological change. The origin of subdued linear forms with high clay and carbonate content involved deflation of sands, pelletal clays and carbonates from lower dune flanks and swales in a manner resembling that known to have occurred in the building of clay-rich lunettes. As well as controlling dune form, the original parent material, especially variations in the clay and carbonate content, may also have been responsible for affecting the varying degrees of rubefaction and consolidation evident between subdued linear forms and steep, high, irregular siliceous dunes.

In the southeastern region up to 2 m of fine grained sediment has been deposited as an airborne dust component derived during the building of the dunefields to the west.

Elliptical to sub-circular lunette lakes, in the regularity of their outlines, reflect the influence of surface water derived mainly from catchments outside the region. By contrast, irregular groundwater lakes with abundant coarse and fine grained gypsum (copi) occur in areic areas unconnected to surface drainage.

The scientific, educational and recreational importance of this region, located centrally to the large urban populations of southeastern Australia, demands that consideration be given to reserving large areas as parks or wilderness area; these may be allocated to multipurpose use in a way that ensures public access under suitable management.

INTRODUCTION

The physiographic province described in a general way by the term *Mallee* refers to those semi-arid plains of southeastern Australia characterized by extensive sand ridges on which eucalypts with a particular growth habit form the dominant cover. In these trees of relatively low stature, a cluster of branches emerges from a ligno tuber below ground level. From this specific connotation the term has come to describe entire regions where such eucalypts are common, the most extensive being the western portion of the Murray Basin extending from near Hillston in the north and Swan Hill in the south, west across the South Australian border to the Flinders Ranges.

This paper is concerned mainly to present a new map of the landforms of northwestern Victoria and southwestern New South Wales (Fig. 1). By integrating such evidence across the state boundary, we hope to provide a better understanding of this region, one that is as remarkable in the diversity of fluvial, aeolian and lacustrine landforms it preserves as in the complexity of Quaternary changes it records.

Few areas possess such a compact array of distinctively 'Australian' forms. A variety of continental dunes are represented in an area that includes the tributary junctions of southern Australia's main river systems. The Loddon, Wakool, Murrumbidgee and Darling Rivers all join

* Department of Biogeography and Geomorphology, Research School of Pacific Stuides, Australian National University, P.O. Box 4, Canberra, A.C.T. 2601.

the main Murray trunk stream within the boundaries of the map whilst the Anabranch of the Darling with its great chain of lake-lunette basins presents us with a fine example of forms peculiarly Australian. These major drainage lines converge within the region that once formed the most easterly extension of active desert dunes. The variety of processes thus involved have combined to produce a distinctive diversity of semi-arid landscape features. Since E. S. Hills drew attention to these features in 1939, we have only recently begun to comprehend the magnitude and complexity of the events involved in their formation. The map is designed to assist in that enterprise.

For many, the value of the map may lie more in the features it portrays than in the notes that accompany it. Therefore the comments which follow do not seek to provide a full and comprehensive account of the region but rather to describe some of the more salient points that underlie the logic of the land classification used, and contribute in a general way towards understanding the nature and the origin of the landforms depicted.

Previous surficial maps of this region have been confined to northwestern Victoria, notably the early description by Hills (1939), followed by the later land systems studies of Rowan and Downes (1963) and the geological investigations of Lawrence (1966). More recently Hills (1975) has re-examined the Mallee as a distinctive physiographic province. In its eastern part the map overlaps with the geomorphic map of the Riverine Plain (Butler *et al.* 1973). In the northwest the Darling river lakes have appeared on topographic and geologic maps of New South Wales (Geological Survey of N.S.W. — 1:250,000 series Manara and Menindee sheets). In producing this map we have drawn upon the evidence provided by earlier workers and have contributed new data principally from the New South Wales section. The boundaries chosen for the map are 141° and 144° east longitude and 32° and 36° south latitude giving a total area of some 115,000 km^2 (Fig. 2).

METHODS

Data were drawn from pre-existing maps, from photo-mosaics and from stereoscopic examination of aerial photographs checked by extensive ground traverses. An indication of map reliability is provided in Fig. 3. Information derived in this way was compiled initially at a scale of 1:250,000. In the process of reducing to final publication scale, a compilation was made at 1:500,000 identical with

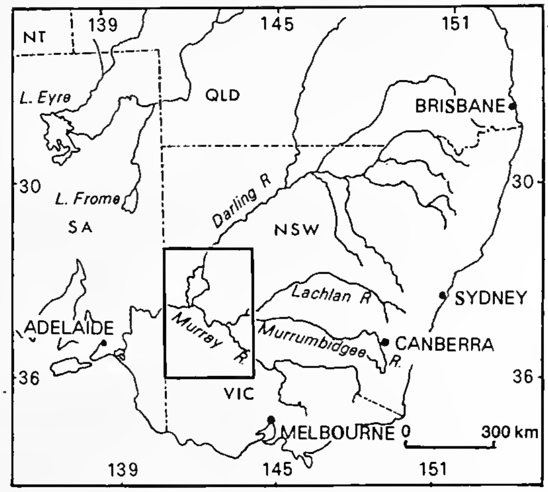


FIG. 2 — Location diagram. Inset shows area covered by Fig. 1.

that of the Geomorphic Map of the Riverine Plain (Butler *et al.* 1973). For research purposes this intermediate scale may prove more useful than the final publication at 1:1,000,000. Dyeline copies at the intermediate scale are available on request from the authors.

Classification and Mapping Criteria

The classification adopted in constructing the map is primarily a genetic one based on the distinctive expression of landforms of fluvial, aeolian and lacustrine origin. Such classifications based on mode of origin can rarely be applied with complete unambiguity. Throughout this region the characteristic expression of landforms related to specific processes reduces the dangers normally associated with a genetic classification. However problems occur in mapping areas of clay plain, the origin of which cannot be related specifically to any one process. Thus in the map legend two categories, namely *clay plain* and *clay plain with sand cover*, are not designated in terms of the processes that controlled them.

Seven aerial photographs are included to illustrate some characteristics of the geomorphic units mapped and examples of the variations which may occur within them.

GENERAL DESCRIPTION OF THE REGION

Geologic Setting

The present landforms and sediments which constitute the Mallee Region form the western portion of the Murray Basin of southeastern Australia. The sands and dunefields of Quaternary age overlie a predominantly marine sequence of Tertiary sediments (see Macumber 1978). To the

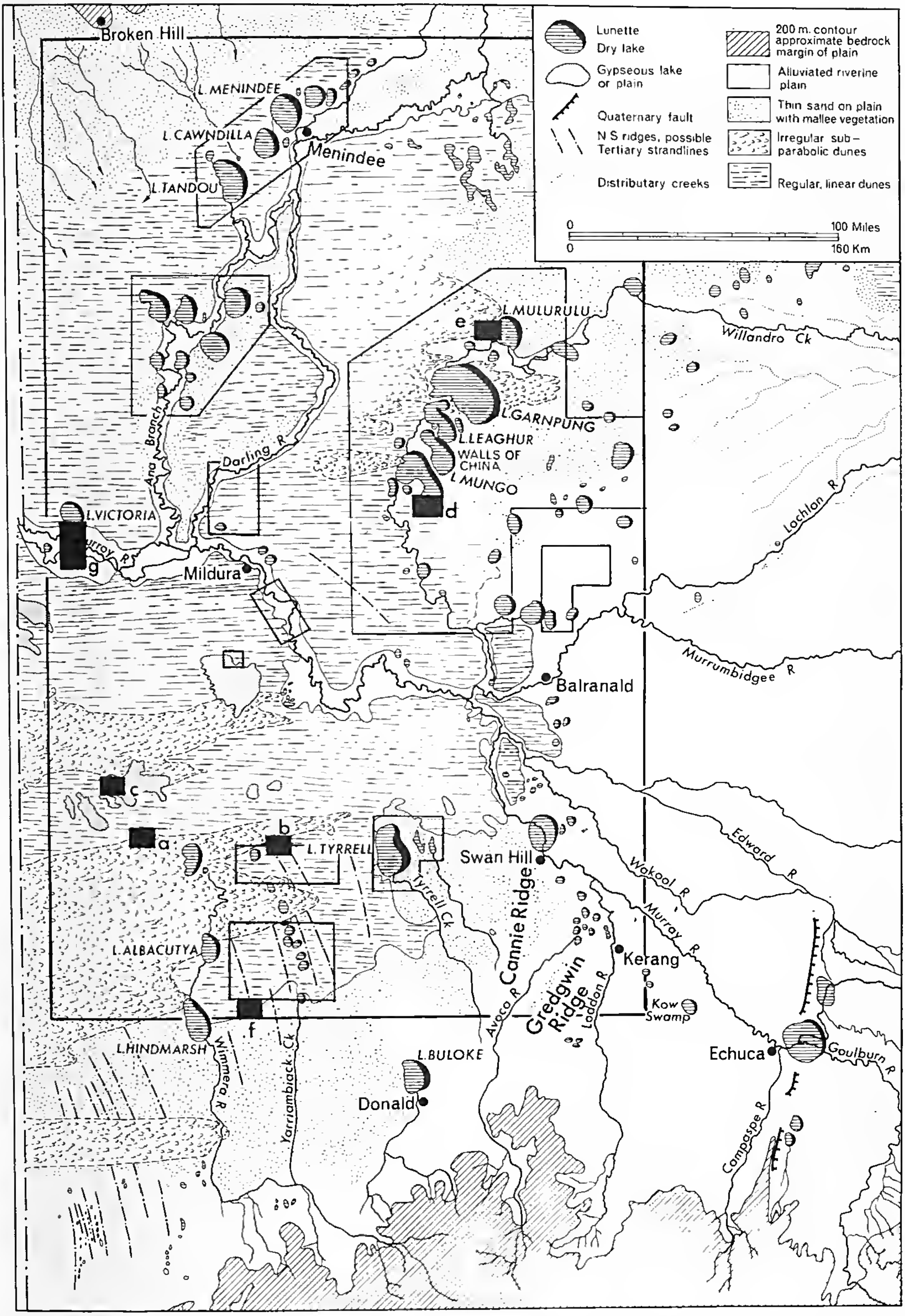


FIG. 3 — Regional map of Murray Basin. Large insets — areas examined by stereoscopic coverage. Small numbered insets — key to location of plates: a = Pl. 2(1), b = Pl. 2(2), c = Pl. 3(2), d = Pl. 3(1), e = Pl. 4(1), f = Pl. 4(2), g = Pl. 5.

east of the Mallee, the Riverine Plain of northern Victoria and southern N.S.W. (Butler *et al.* 1973, Pels 1969a, Lawrence 1976) forms the eastern portion of the Murray Basin. There too deposits of Quaternary age overlie Tertiary alluvial and lacustrine sediments.

The geological history of the Murray Basin has been summarized by Pels (1969a) and Lawrence (1976). A lower Tertiary marine transgression in the Murray Basin led to the deposition of calcareous sands, marls and limestones. A short regression was followed by an extensive transgression. During the subsequent regression in the upper Miocene to lower Pliocene a widespread, well sorted silt and fine to coarse grained quartz sand was deposited in littoral to near-shore conditions, the Parilla Sand of Firman (1965). On the surface of the Parilla Sand, a series of sub-parallel strandline ridges were formed as the sea retreated from the Basin (Blackburn 1962). These may be traced to the present coast in South Australia.

The Parilla Sands have had a marked influence on subsequent Quaternary sedimentation both as a source of sand for the aeolian units and as a structural control in that the sub-parallel north-south ridges control drainage lines and the distribution of lakes. Much of the inter-ridge laterized surface of the Parilla Sand is overlain by early Quaternary lacustrine sediments — the Blanchetown Clay and the Bungunnia Limestone (Firman 1965, Lawrence 1976).

Relief

The Mallee forms a broad plain interrupted by minor relief provided as dunes, channels or north-south ridges. Its elevation varies generally between 50 and 80 m above sea level with the southern portion, closer to the ranges, somewhat higher. Greatest relief contrast occurs in the northeast where the Manara Hills rise some 120 m above the Plain. The Darnick and Manfred Ranges are more subdued, emerging only 20 to 30 m. In the south the structurally controlled Cannie and Gredgwin ridges (Fig. 3) rise some 40 m above the dunefield but only 20 m above the adjacent clay plain.

Throughout the region lake basins are common, with depressions up to 10 m deep and adjacent lunettes rising 30 to 40 m above the plain on the larger examples. However on the numerous small basins lunette relief is usually less than 10 to 15 m.

The irregular, sub-parabolic dunefields have topographic relief with crests rising to 10 m above the regular dunefield in the north and up to 50 m in the Big Desert.

The NNW-SSE strandline ridges form subdued highs in the regular dunefields, commonly carrying lake depressions or river channels within the inter-ridge corridors. Where such ridges are buried by the sub-parabolic dunefield they tend to lose their topographic expression.

Climate

The Mallee Region lies on the southeastern margin of the arid zone and is characterised by a semi-arid climate, warm with moisture deficiency, in every season. Mean annual rainfall data are shown in Fig. 4. Precipitation decreases in amount and reliability towards the northwest. Rainfall distribution throughout the year is relatively even with a slight winter dominance in the south and equally small summer dominance in the north. Evaporation greatly exceeds precipitation; annual pan estimates increase from 1260 mm at Lake Boga in the southeast to 1640 mm at Menindee in the northwest.

Summer temperatures are high, commonly exceeding 40°C in January and February; winter temperatures are mild with maxima around 15-17°C and relatively low frost incidence at 5 to 15 days per year. Winds throughout the region reflect the dominance of the westerly system. Strong northerly and westerly components are represented throughout the year, with infrequent north-easterlies and easterlies. Dry northerly winds blowing from the arid continental interior sometimes produce severe summer dust storms, especially during periods of drought.

Vegetation

The vegetation of the Mallee Region is dominated by the eucalypt association from which it derives its name. This consists of low, multi-stemmed eucalypts (e.g. *E. oleosa*, *E. dumosa*) with shrubs and grasses. Where the regular dunefield becomes more open, with subdued relief, the fine grained swales carry fewer eucalypts with more grasses and other tree species, especially *Acacia*, *Casuarina*, *Hakea* and *Heterodendrum*. Stands of native pine, *Callitris* sp., are also frequent on some sandy areas.

The clay plains and lake floors tend to be treeless and are dominated by chenopodiaceous shrubs and grasses, with salt bush communities extending over large areas. River channels and flood plains are characterized by large eucalypt species, principally *E. camaldulensis* and *E. largiflorens*.

Throughout the region areas bare of vegetation due to development of scalds or blowouts are common, especially where intensive land-use has

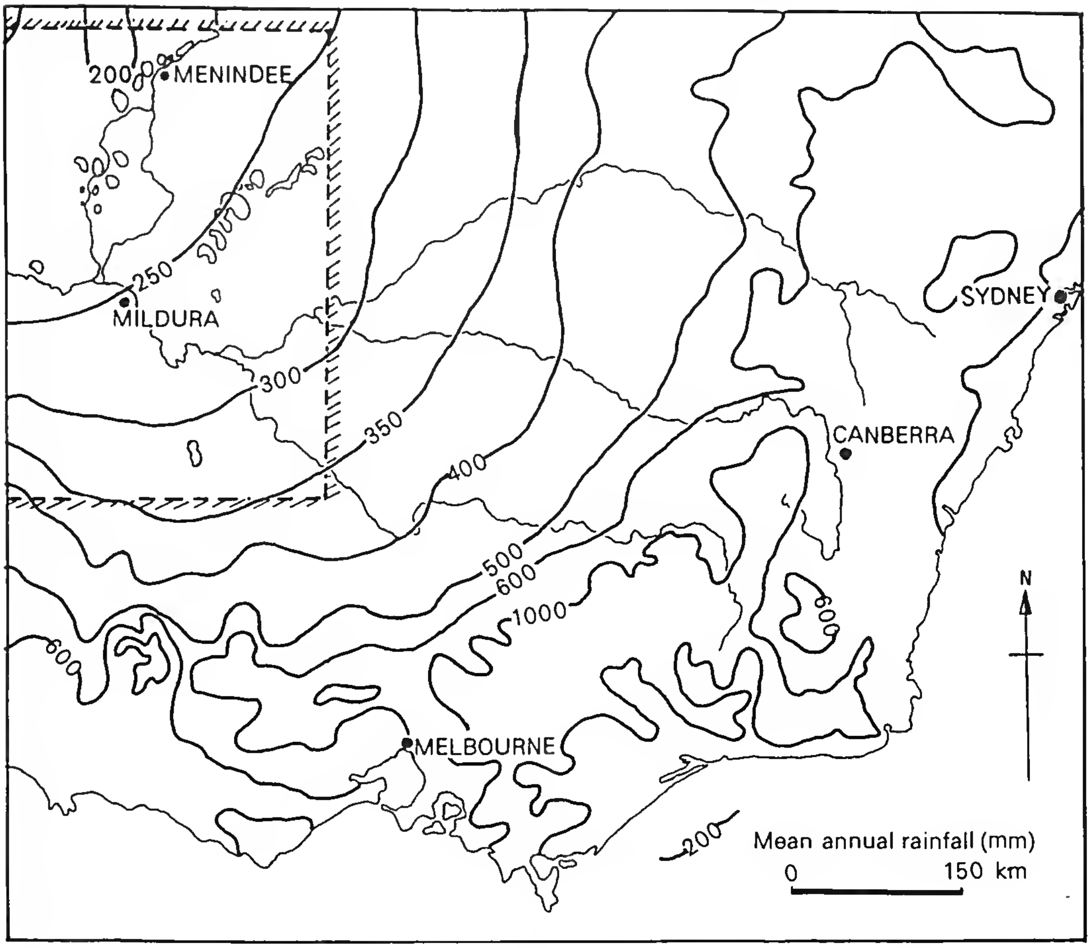


FIG. 4 — Map showing mean annual rainfall isohyets for southeastern Australia.

lead to widespread clearing of vegetation (Rowan & Downes 1963).

DESCRIPTION OF GEOMORPHIC UNITS

NORTH-SOUTH RIDGES

The presence of elongate ridges in the Victorian Mallee was recognized by Hills (1939) who showed their clear expression in contour patterns (Pl. 2(2) & 4(2)). On topographic maps the ridges are expressed as broad elongate features trending NNW-SSE as in the area east of Rainbow. Their presence is further emphasized on such maps by the complex channel network installed by the Victorian government during the depression years, to carry fresh water supplies from southern catchments to provide a reliable source to each landholder in the region. Many of the major channels run NNW. following the trend of the ridges (Pl. 4(2)).

Following soil surveys of similar features in the southeast of South Australia and southwestern Victoria, Blackburn (1962) postulated these ridges represented relict Tertiary shoreline features similar to those closer to the coast where the marine influence is clearly established. Although their exact manner of emplacement is not well understood, the ridges clearly represent successive strandline positions during retreat of the late Tertiary sea.

The map shows the occurrence of four ridges not previously defined in southwestern New South Wales. Although they are mainly covered by dense mallee eucalypt scrub the ridges are visible on mosaics and aerial photographs. The most prominent, north of Lake Benanee, has a broad flattish crest some 3 km wide that sweeps in a broad arc to the northwest.

Further inland the *en echelon* arrangement of the Willandra lake basins and the common NNW-SSE alignment of river channels may reflect the influence of similar structures now too subdued to

be recognised in the topography. The presence of sediments resembling Parilla Sands in cores we obtained from 15-20 m beneath the floor of Lake Mungo together with outcrop there of silcrete cementing well sorted beach-like sands provides *prima facie* evidence that the limits of Tertiary transgression may have extended to the Willandra Lakes region. Indeed the easterly limit of quartz dunes in the southern region covered by the map lies close to the limits of marine transgression (Macumber 1969b). The marine sandy facies that underlies the core of the north-south ridges (Parilla Sands in the sense of Macumber 1969b, or Diapur Sandstone of Lawrence 1966) probably contributed a large component of source material to the linear dunes.

Drainage

The region demonstrates three types of drainage characteristic of arid and semi-arid environments. Firstly, throughout the greater part of the area, there is no contribution from surface runoff to overland flow. This areic aspect is reflected in the absence of channels from east and west of the Darling and from the entire area of northern Victoria north of Lake Tyrrell (Pl. 2(1) & 3(2)).

Secondly, the streams in the southern region, namely the Wimmera River, Yarriambiack, Tyrrell and Lalbert Creeks, which rise in the better watered hills to the south, are endoreic systems in that they lose their water as they flow north, and terminate in a string of lake basins amongst the Mallee sandhills (Hills 1975).

Thirdly, only the major rivers carrying waters from the wetter areas of the southeastern highlands and from southwestern Queensland succeed in crossing the plain (Pl. 5). Both the Murray and the Darling tend to lose water as they traverse the region to the west, a common feature of exoreic drainage in arid and semi-arid regions elsewhere.

Two additional aspects of the drainage are worthy of note. Firstly, the absence of lakes on the Darling River channel passing through Pooncarie is in marked contrast to the abundance of such features along the Anabranch channel. The fluvial stratigraphy, age and regime associated with anabranch formation upstream from Menindee is discussed elsewhere (Bowler *et al.* 1978).

Secondly, the dry channel of the Willandra Creek which wends its way through the field of linear dunes south of Outer Arumpo presents mute testimony of past hydrologic episodes in which the availability of surface water was much greater throughout the region than it is today. This channel last carried overflow discharge from the lakes some 16-18,000 years ago (Bowler 1971). Its preservation through the linear dunefields provides an excellent example of landscape longevity in this region.

Linear Dunes

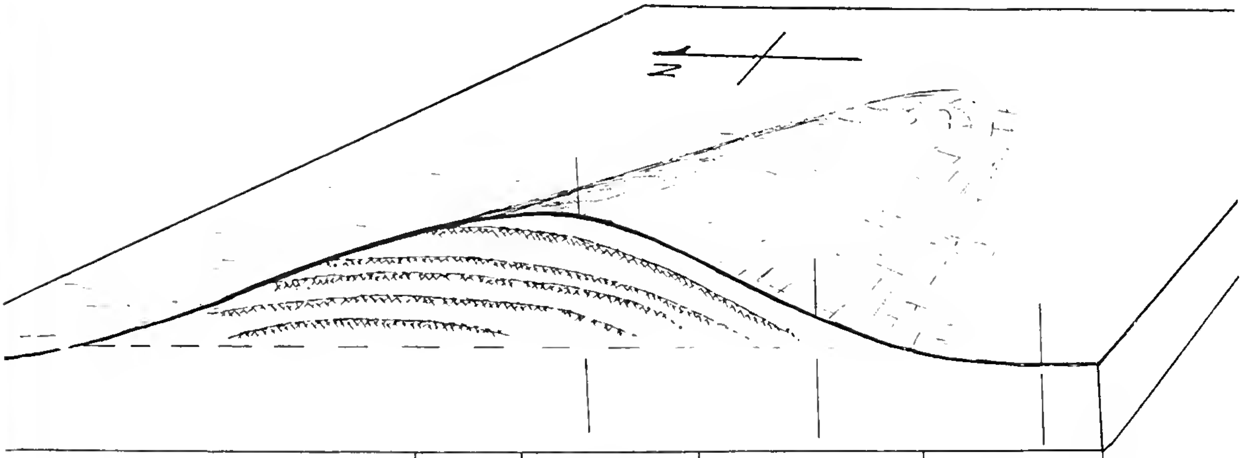
Low elongate sand ridges form the most characteristic landforms extending from north to south throughout the region. These dunes comprise relatively straight regular forms maintaining a west to east orientation reflecting the resultant direction of the controlling winds. In characteristic expression such as west of Swan Hill (Pl. 2(1) & (2)) they maintain a relatively uniform spacing from 0.2 to 1.2 km apart, varying in length from 0.5 to 3 km, but typically about 1.5 km long.

In section, the dunes possess low, rounded, subdued crests rising usually 2 to 6 m above the swales with occasional relief to 10 m. The slopes are gentle, with the south-facing side usually steeper, producing a slightly asymmetric cross-section (Hills 1939, Churchward 1963) as illustrated in Fig. 5. Sediments forming the dunes constitute the Woorinen Formation of Lawrence (1966).

In their composition the linear dunes contain a relatively high percentage of clay and calcium carbonate. Studies by Churchward in the southern region northwest of Swan Hill record clay values commonly reaching 20%, with an average composition of about 7-10% within dunes but reaching higher values in swales (Fig. 5). Carbonate in the same region varies from peak values of 14% in the uppermost (Kyalite) layer to an average composition of about 5% (Churchward 1963). The carbonate content which remains relatively high throughout the linear dunes of northwestern Victoria diminishes to the north through New South Wales, although the clay component remains relatively high throughout.

From crest to swale the linear dunes display strong catenary development. Clay and carbonate content increase down slope reaching maximum values within the swales where fine grained clay loam is often associated with a carbonate pan or calcrete. This catenary development contributes to the characteristic expression of the linear dunes in which the low, subdued forms with rounded ends appear to rise like submarines partly submerged in a sea of fine grained sediment (Fig. 5). This impression is enhanced by the selective colonization of the well drained crests by mallee eucalypts with more open grassland developed on the fine grained swales.

In vertical section the linear dunes throughout the southern half of the region contain a series of



DEPTH	Clay	$CaCO_3$	Clay	$CaCO_3$	Clay	$CaCO_3$
0–50cm	5	1	15	1	17	3
50–100cm	16	4	25	20	29	36

FIG. 5 — Perspective diagram showing relationship of internal soil horizons to form of subdued linear dune. Geometry of buried soil horizons (not necessarily groundsurfaces), extrapolated from photograph of Nyah West railway cutting. Analyses refer to catenary data; the two sets of figures refer to percentage clay and carbonate respectively on crestal, midslope and swale sites. Profile data generalised after Rowan and Downes (1963) and Churchward (1963).

calcareous paleosols (Hills 1939, Churchward 1961) indicating a long history throughout which the dune form has been perpetuated during each successive phase of aeolian reactivation (Fig. 5). Stratigraphic studies of the buried soils suggest that the last major phase of dune growth occurred some 15,000 years ago (Bowler & Polach 1971), following a long period of stability during which a previous paleosol had formed (the *Speewa* of Churchward 1961).

Virtually all the linear dunes are relict features which were stabilized by thick vegetation cover until the time of European development. Some have been reactivated, especially where the clearance of the Mallee woodland was followed by long droughts as in the 1930s, during which cultivation resulted in widespread sand mobilization. The redeposited layer often forms a thin blanket across the dune surface, a layer that corresponds to the *Piangil* of Churchward (1961).

A variation of the regular longitudinal dunes occurs near the boundary between linear and irregular, sub-parabolic dunes; it forms a transitional phase between the two groups. Such dunes are found west of Outer Arumpo and south of the Sunset Desert where long sharp-crested, siliceous dunes maintain regular linear forms for more than 5 km (Pl. 3(2)). In contrast to the typical low rounded dunes, they are higher, more closely spaced and maintain a well sorted sand texture from crest to swale; the catenary transition from coarse to fine is lacking. Moreover the preservation of steep, sharp crests indicates the development of sand-slip faces during mobilization, a feature that is significantly absent from the subdued linear forms.

IRREGULAR, SUB-PARABOLIC DUNES

Large fields of steep, irregular siliceous sand dunes extend as elongate west to east lobes particularly well developed in northwestern Victoria and east of the Darling River in New South Wales. Within such areas a wide variety of forms is represented. Although generally more irregular than the linear varieties they often transgress, and sometimes referred to as 'jumbled' dunes, they possess a degree of order reflecting the influence of the prevailing westerlies which formed them (Fig. 6). Thus east of Lake Garnpung closely spaced parabolic forms, interfering with each other and resulting in irregular or sub-parabolic outlines, are oriented with their apexes pointing east. Within the Sunset and Big Desert regions, the plan geometry of dune crests is less regular but even here the influence of the westerly vector finds expression (Pl. 2(1) & (2)).

Within this group of irregular and sub-parabolic forms, crests frequently rise more than 10 m above swales. Slopes are steep and crest to crest distances

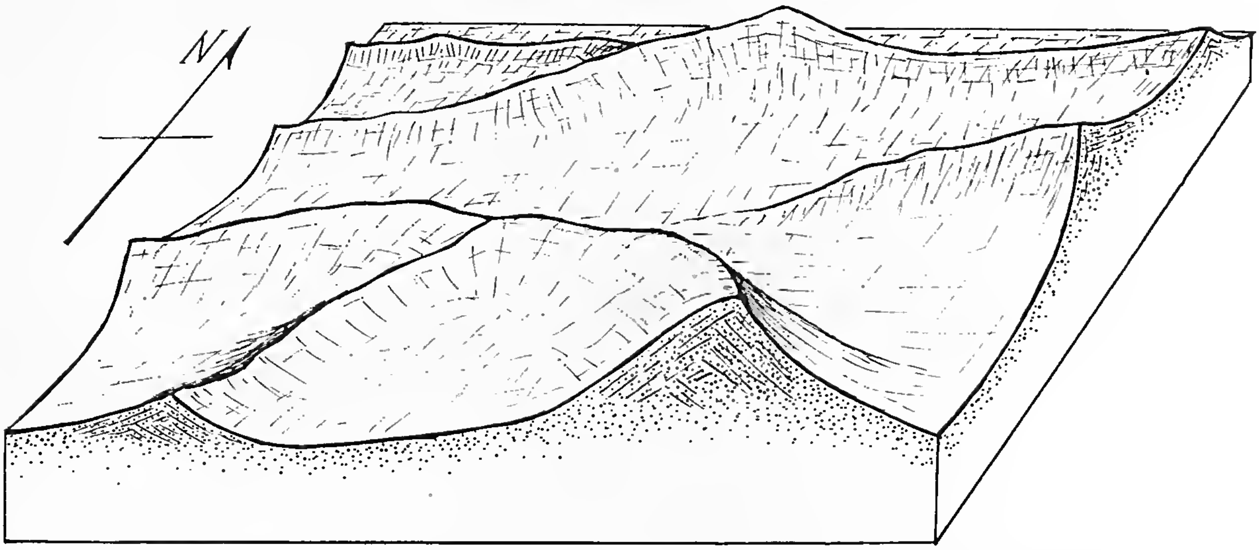


FIG. 6 — Idealised perspective diagram (without mallee scrub cover) through irregular to sub-parabolic dunes showing relationship between form and internal structure. Deep siliceous quartz sands average about 2-3% clay with 0.5% carbonate according to Rowan and Downes (1963).

are extremely variable, though dune spacing is much closer than in the open, linear forms.

Sediments of the sub-parabolic sand dunes are highly siliceous. Carbonate is usually absent; when present it occurs only in minor amounts sometimes as soft chalky elongate concretions developed after tree roots. Similarly the high percentage of clay which characterizes the catenary profile of the linear forms is absent from the sub-parabolics; in these the profile from crest to swale consists of relatively uniform siliceous sand (Fig. 6).

Sand Plain

Areas designated as sand plains occur as two distinctive and widely separated areas. In the northeastern sector (Pl. 4(1)) and in a discontinuous belt following the Darling River and the Anabranch, an undulating sand plain is characterized by irregular sand accumulations equivalent to the hummocks of Rowan and Downes (1963). These are sub-circular in plan, occurring commonly as a complex of mounds varying from less than 100 m to 3 km in diameter and from a few metres to over 30 m in elevation. Hummocks are formed from a variety of materials ranging from sands to sandy clays with evidence of layered paleosols and catenary profile differentiation (Rowan & Downes 1963).

The second area mapped as sand plain occurs in the southeastern corner lying on either side of the Avoca channel, forming the surface expressions of the Gredgwin and Cannie ridges (Fig. 3). Macumber (1969b) has demonstrated the presence there of Tertiary marine sandstone bounded on the east by a north-south fault with uplift on the west. There are certain difficulties in including these areas in the sand plain category in that their surficial materials combine components both of sand and finer clay loam. But they are included rather than establish an additional unit.

Lunette

This region includes some of the best examples of lunettes to be found in Australia. Indeed, in first defining such features from northern Victoria, Hills (1939, 1940) drew heavily on his experience of Mallee examples.

Their occurrence as smooth, crescentic, transverse dunes on the eastern side of lake basins (Pl. 3 (1)) is well known from other parts of southern Australia. They record complex oscillations of past hydrologic sequences varying through periods when deep and relatively fresh water concentrated clean quartz sands on eastern beaches for contribution into the down-wind dune. Later, during more saline conditions associated with drying, gypseous clay pellets were transported by saltation from exposed lake floors to provide the smooth surfaces most characteristic of their present form (Bowler 1973).

The size of the lunette generally bears a strong relationship to the size of the basin from which its materials were derived. Thus on small lakes less than 1 km in diameter, the lunette may be only a

few metres high, whereas on larger basins they frequently rise to more than 15 m; they reach to 30 m above the lake floor on the Chibnalwood Lakes on the Willandra Creek and to 40 m on Lake Tyrrell.

Lunettes are often composed of multiple stratigraphic units. On some lakes these are laterally separated from each other (Pl. 3(1)), producing a concentric system as on many of the Darling River lakes and on Lake Tyrrell and Lake Albacutya. On others the units are superimposed vertically, one on top of the other, to produce a single complex ridge such as on Lake Mungo and Lake Tutchewop.

Lunettes throughout this region are exclusively relict features relating to hydrologic events of late Pleistocene time. Dates available from the last episode of lunette building cluster in the range between 19,000 and 15,000 B.P. with many showing evidence of synchronous development between 17,000 and 16,000 as at the Willandra Lakes, Tysons Lake and Lake Albacutya (Bowler 1976).

The sediments that comprise these features are closely related to the hydrologic conditions that formed them. Those that occur in close proximity to major drainage channels tend to be dominated by deep, freshwater facies which contributed large quantities of quartz sand to the shoreline dune. Thus the lunette on Travellers Lake on the Darling River consists entirely of quartz sand, suggesting this basin never experienced the hypersaline environment necessary for the formation of the clay-rich lunette materials. Others such as the Chibnalwood Lakes (Pl. 3(1)), Lake Tutchewop and Lake Albacutya contain relatively high percentages of gypsum in their upper units, consistent with their final stage development having taken place under saline conditions.

Stratigraphic and chronologic analysis of lunettes has been particularly instructive in helping demonstrate the complex palaeohydrologic history, the legacy of which is preserved in the landforms of this region (Bowler 1971, 1973, Macumber 1970, Gill 1973). Moreover the lunettes provide a most favourable environment for the rapid burial and preservation of archaeological remains relating to periods when early Man camped on the shores of the predominantly freshwater lakes. Lunettes throughout this region have provided one of the richest sources for the evidence of prehistoric Man and vertebrate remains in southern Australia. Sites such as Menindee, Tandou, Nitchie, Lake Victoria, and the variety of Willandra sites centred on Lake Mungo have become hallmarks in the literature of Australian prehistory. Furthermore the archaeological potential and faunal content of lunette sites have only just begun to be adequately explored. In future studies, the lunette lakes of the Mallee Region will continue to yield much new information.

Lake Floors

Lake basins have been represented on the map where the presence of lowlying areas is defined by a relatively sharp break in slope on the western margin representing an ancient or modern cliff line (Pl. 3(1) & 4(1)). On their eastern side such depressions are enclosed by lunettes so characteristic of lake basins across southern Australia. The basins are typically smooth and elliptical, often kidney-shaped in outline, with the long axis oriented N.-S. or NNW.-SSE.

All large basins are associated with drainage lines which contributed the surface waters so important in shaping their outlines. Thus the Murray River has groups of lunette lakes marginal to its channel as at Robinvale, Hattah and Lake Victoria (Pl. 5). Similarly the numerous lakes of the Anabranch and the Willandra Creek owe their characteristics to past high stage surface flows of the Darling and Lachlan Rivers respectively. Other large lunette basins such as Lake Tyrrell and Lake Albacutya occur as terminal systems of the Tyrrell Creek and Wimmera River. The numerous basins near Hatfield and Balranald occupying regions where no surface water is available today represent a legacy of past environments that were much wetter than the present climate, at least in terms of runoff if not in absolute precipitation.

Most lake basins are dry, although some are filled artificially for use as water storage basins. Two types of such use are involved: one for the storage of freshwater as at Menindee, Kangaroo Lake and Lake Charm near Kerang; secondly, some are now being used as evaporation disposal basins for saline groundwater as at Lake Tutchewop and in a scheme presently being considered by the State Rivers and Water Supply Commission of Victoria for Lake Tyrrell.

Some lakes, such as those on the Darling River, are filled by ephemeral flooding. These drain back into the river attenuating the passage of the flood wave. Others, such as Lake Tyrrell, intersect groundwater systems. With its characteristic salt encrusted surface Lake Tyrrell forms the largest salt lake in Victoria.

Sediments on the floors of most dry basins consist exclusively of fine grained materials

dominated by clays, with silts and sands more prominent on the eastern downwind margins. The clay plains sometimes possess large desiccation cracks where montmorillonite forms a substantial component in the clay mineral assemblage. Exchangeable salts remain high; this is reflected in the nature of the salt tolerant vegetation that colonizes the lake floors. Where the floors have been modified substantially by later alluviation or other processes they are shown on the map as alluvial or clay plain units.

The western margins of the basins frequently truncate the easterly extension of linear or irregular dunes. Rarely do such dunes transgress onto the lake floors, a phenomenon which Bowler (1971) attributed to the presence of water in the lakes simultaneously with the advance of the dunes. Exceptions occur in the Willandra Lakes where lobes of irregular dunes transgress across the ancient shorelines of Lake Garnpung and Outer Arumpo (Bowler 1971). In the southern portion of the map, some lunette lakes are apparently submerged beneath transgressive dunes of the Big Desert along the course of Yarriambiack Creek, providing a rare example of dune encroachment across lake floors.

Gypseous Lake Floor or Plain

Landforms of this category occur in the most northwesterly sector of Victoria, north of the Big Desert, and in N.S.W. west of the Anabranch. The occurrence of gypseous deposits indicates that in the past these low lying areas have been sites of groundwater evaporation. They are characterized by asymmetrical irregular shapes (Pl. 3(2)) in contrast to the lunette basins where abundant surface water has helped produce smooth symmetrical outlines. Furthermore on aerial photographs the surface within the depression rim possesses irregular convolute patterns, often with a north-south orientation (Pl. 3(2)). These in part reflect past wind sculpturing of gypseous material on the floors of areas such as the Raak Plain where gypsum is mined commercially. Low aeolian ridges of white fine grained gypsum (copi) are common.

The occurrence of irregular gypseous and elliptical lunettes lakes are mutually exclusive. Thus, in northern Victoria, an east-west line from Ouyen to Murrayville effectively separates the irregular gypseous basins in the north from the regular elliptical lunette basins in the south. The same line also forms a boundary between areas of no surface drainage and the terminal drainage systems of the Wimmera, Yarriambiack, Tyrrell and Lalbert Creeks with which many lunette lakes are associated. The gypseous lakes on the other hand occur in regions remote from drainage lines, where the hydrologic contribution was restricted in the past as it is today to local runoff and especially to groundwater inflow.

Upper Alluvium

In the area adjacent to the Darling-Murray junction a sequence of alluvial terraces is inset below the general level of the aeolian plain. The upper terrace lying above the general level of flooding is designated upper alluvium (Pl. 5). It corresponds to the Neds Corner Land System of Rowan and Downes (1963) and extends up the tributary system of the Darling and Anabranch channels. Although it is present in the Murray Valley upstream from Mildura it has not been identified at the mapping scale. This unit is inset into, and therefore postdates, the inception of the linear dunefield. Whilst the surface cover of sand and clay may in part be aeolian, the sediments comprising this terrace are dominantly fluviatile. Near Mildura, the unit possesses a calcareous red brown earth soil and is in part equivalent to the Green Gully ancestral river phase further upstream in the Murray Valley. However, since we are not able to differentiate between all terrace levels within the alluvial belt, this unit should not be taken to indicate chronologic continuity. The unit as mapped includes alluvial sediments of different ages.

Lower Alluvium

This unit which follows the major drainage channels throughout the region is generally equivalent to the modern floodplain. Downstream from Wentworth it maintains a relatively constant level below the higher level designated as upper alluvium (Pl. 5).

Soils developed on the sandy loams of this system are generally grey acidic profiles equivalent to the minimal prairie soils described by Butler (1958). The unit represents the stratigraphic equivalents of the youngest ancestral river phases of Pels (1969b). The large areas designated as lower alluvium upstream from the Walkool Junction almost certainly include areas of older alluvial deposits, areas unable to be differentiated at the mapping scale adopted. Moreover, in the same region the differentiation between alluvial clay and clay plain of undesignated origin remains somewhat arbitrary, but wherever surface drainage patterns show the influence of overland flow and associated deposition these plains have been classified as alluvial.

Clay Plain and Clay Plain with Sand Cover

Within the map categories, two groups of non-genetic origin have been specified, clay plains and clay plains with sand cover. Since the latter constitute a slightly modified version of the former, discussion of their distribution and significance may usefully be considered together. Lying east of the dunefields they constitute large areas between major drainage lines. On the Geomorphic Map of the Riverine Plain, the clay plains east of Sea Lake are shown as 'dominantly of aeolian origin' by Butler *et al.* (1973). Whilst the surface sand cover is demonstrably reworked by wind, the origin of the extensive surface clay of the wheatlands region in the southeast of the map remains in doubt. The relative contribution of sediment from former lacustrine, fluvial or aeoloian episodes is not known.

This unit corresponds generally to the Culgoa Land System of Rowan and Downes (1963). The clay plains, often with the strong development of gilgai, originally carried a cover of eucalypt scrub. This has now been cleared throughout most of the region for grazing and cultivation.

The clay plain with sand cover represents a unit of restricted extent transitional between clay plains and linear dunefields. Its boundaries in the southeast are clearly related to the topographic expression of the north-south ridges (Pl. 4(2)).

Bedrock Hills

Pre-Tertiary outcrops occur in the northwest of the region where the Manara, Darnick and Manfred Ranges form inliers of Upper Devonian sandstone protruding through the Tertiary and Quaternary cover. These form stony ranges rising above the surrounding plain. Tertiary erosion of these and similar rocks probably contributed substantially towards the supply of quartz sands that now mantle the greater part of the plains surrounding them.

DISCUSSION

Origin of Dune Forms

a. *Linear dunes*. Variations in the form, sediments and stratigraphy of the different dune types help provide clues concerning their origins. This is particularly relevant in the case of the subdued linear dunes formerly regarded as being degraded remnants of once larger, steeper forms. Within such dunes (Fig. 5) successive layers separated by buried soils indicate the retention of form similar to that of the present day despite successive episodes of re-mobilization (Hills 1939, Churchward 1961). Moreover the abundance of clay and carbonate within their soil profiles even on crestal sites suggests that new layers added during arid episodes were derived from fine-grained calcareous sediment in the swales as suggested by Rowan and Downes (1963). This is confirmed by the presence of sand-sized clay aggregates observed in thin-sections we have examined through such a dune at Nyah West. The aggregates bear a resemblance to some developed on salinized depressions, the importance of which has been documented for lunette formation (Macumber 1970, Bowler 1973). The extent to which they have resulted from normal erosion of pre-existing soils or were assisted by saline efflorescence on flanks and swales cannot be ascertained. However, the presence of clay pellets preserving traces of original depositional fabric implies an important relationship with the clay lunette forming processes.

This phenomenon is consistent with the age postulated for the last episode of linear dune mobilization believed to lie between 25,000 and 16,000 B.P., an episode that followed a wet period in which watertables and lakes were considerably higher than today (Bowler *et al.* 1976). With a reversal of the hydrologic budget towards drier conditions groundwater salts would have accumulated in the swales where abundant surface water would previously have produced downward leaching. With decreased runoff, swales and lower dune flanks may have become sites of groundwater or soilwater evaporation loss. Any salts thus concentrated would have contributed to the development of carbonate pans and to the efflorescence responsible for breaking clays into pellet sized aggregates for deflation onto the flanks and crests of the adjacent dunes.

One further line of evidence supports this notion of dune growth. Each successive aeolian unit was deposited in approximately conformable attitude across the pre-existing topography. Although individual bedding planes are not preserved, this structure is strongly suggestive of the laminar subhorizontal bedding so frequently found within clay-rich lunettes (Bowler 1973). Dune growth by mobilization under the influence of steep migrating sand-slip faces would have produced aeolian units of variable thickness and with sharpened crests. The absence of such features reflects initial growth patterns rather than subsequent degradation. Thus the accretion process resembles the formation of the transverse clay-rich lunettes which, throughout this region, were actively forming simultaneously with associated longitudinal dunes in the interval centred on the period between 17,500 and 16,000 B.P. (Bowler *et al.* 1976).

Throughout the remobilization process pre-existing linear dunes remained bonded by compact clay and calcareous soil horizons. Not only did the form remain stable with the younger layer draped slightly asymmetrically over the central axis but no significant downwind migration of individual dunes occurred. Thus they have remained short and occur at relatively constant spacing despite a long history throughout late Quaternary time. Unlike the more mobile linear forms of Central Australia they never form Y-junctions, a feature attributed here to their unusual composition and the manner of formation it reflects.

This proposed mechanism of formation can be tested in several ways. Firstly, subdued linear dunes, if formed as a result of salinization after a period of high watertables, will not be found on well drained parts of the landscape. Their absence from the Cannie and Gredgwin ridges may indeed be due to this factor. Secondly, unlike the quartz dunes of the Simpson Desert (Twidale 1972) their regularity will not vary downwind from stream channels. Since their source materials are derived from adjacent swales rather than channel sands, the relative constancy of length and spacing will not vary on either side of intersecting channels. Thus there is no change in the distribution or shape of dunes east and west of the Willandra channel south of Chibnalwood Lakes, a feature that stands in marked contrast to the change in geometry of linear Simpson Desert dunes north and south of the Finke River in Central Australia.

Thus a number of apparently anomalous aspects of the linear Mallee dunes are explained by this mechanism. Their smooth subdued expression represents a depositional influence. The formation of longitudinal dunes by the mechanism proposed here involving salinization of swales has not previously been recorded from Australia, nor are we aware of examples from other arid regions. In this respect they constitute a group of particular interest related to transverse clay-rich lunettes.

b. *Irregular sub-parabolic dunes*. In areas of the sub-parabolic, irregular dunes, neither carbonate nor clay was incorporated into the original parent material; the final expression is markedly different from dunes where such materials were present. Despite the long interval that has elapsed since the last period of mobilization the irrregular and sub-parabolic forms retain their sharpened crests and steep slopes reflecting active crest migration and the development of avalanche sand-slip faces during their formation (Fig. 6). Moreover when mobilized, siliceous dunes involved much larger quantities of quartz sand than is found in the linear forms. The occurrences seem to be dependent on the availability of a large sand supply free of bonding clay and carbonate. Their tendency to occur on the eastern side of alluvial or lacustrine depositional areas represents a further expression of this relationship between form and large sand supply.

Where dated with respect to lacustrine events in the Willandra lakes, two large lobes of irregular dunes were actively advancing on Lakes Garnpung and Outer Arumpo when these lakes were drying between 17,500 and 16,000 B.P. In Victoria, dunes of the Big Desert encroached onto the western shores of Lake Albacutya where radiocarbon dates suggest it too was building its last lunette about 16,000 B.P. (Bowler 1976). Moreover the overflow channel to the north, Outlet Creek, was kept open through the dunefield, suggesting that, as in the Willandra lakes, seasonally high runoff was sufficient to counteract dune movement during this active phase. Thus the last active development of Big Desert dunes occurred synchronously with mobilization of the siliceous dunefield east of the Darling River, an event that coincided with the last glacial maximum about 18,000 to 16,000 years ago.

c. *Vegetation influence*. An additional factor affecting the mobilization and final geometry of dune form concerns the nature of vegetation cover at the time of mobilization. In the case of linear dunes the deposition of a relatively thin blanket of calcareous clayey sand over the pre-existing form suggests that some vegetation cover was retained even whilst the new materials were accumulating. The retention of grasses or low shrubs would be consistent with the stratigraphy of aeolian units and the absence of bedding in such deposits. On the other hand, the formation of irregular dunes involved the destruction of all pre-existing soil profiles from crest to swale, demonstrating a degree of mobilization much in excess of that typified by linear forms. It implies almost complete if not total destruction of vegetation. Thus any factor that effectively destroys vegetation across large areas will be more conducive to the formation of irregular siliceous dunefields.

The lobes that extend to the east downwind of Lake Garnpung and Lake Mungo may owe their origin to a combination of two factors. Firstly, they may have been assisted by increased availability of quartz sand on the downwind side of the lakes. Secondly, the effect of salts derived by deflation from the drying lake floors contemporaneously with the building of the saline lunettes would have assisted in the destruction of vegetation downwind. This in turn would lead to accelerated erosion and

more complete mobilization of pre-existing dunes from crest to swale.

The high, sharp-crested, siliceous variation of the regular linear dunes described earlier (Pl. 3(2)) is related by composition and genesis more closely to the irregular, sub-parabolic forms than to subdued, clay-rich calcareous dunes. The same type of deep sand mobilization with downwind migration of the forms as described for the irregular forms, applies also to the transitional linear forms.

With progressive excavation of swales and additions to crests, dunes will interfere with each other, with consequent reduction of regularity and frequent formation of Y-junctions (Pl. 3(2)).

Colour of Dune Sands

The characteristic colour of sands throughout most of the region is reddish brown (2.5 YR 4/8). In sections through dunes this varies through different pale shades depending on the percentage and distribution of carbonate. However in both the Big Desert and Sunset Desert the siliceous dunes consist of pale yellow to whitish sands in contrast to the reddish dunes they sometimes transgress.

In considering the origin and significance of the red colouration two observations are pertinent. Firstly, wherever dunes can be observed to have taken up the red colour *in situ*, as in source-bordering river dunes, a gradation exists from the surface downwards to progressively paler shades in the parent sands. When seen in thin-section, the rubefaction is due to the development of a clay-rich cutan coating the quartz grains. The clay rim becomes progressively more oxidized to a ferric state in the higher parts of the profile. Secondly, wherever a succession of such dunes exists, as on ancestral rivers and prior streams of the Riverine Plain, the degree of cutan and oxidation development increases with age; the older dunes are reddest and possess the deepest profiles.

The reddening of the sands throughout the Mallee region is seen as a cumulative pedogenic effect inherited over the many thousands of years since the quartz grains were originally deposited by fluvial, marine or lacustrine processes. During each stage of soil erosion and redeposition the red cutan is retained, although at times it undergoes considerable abrasion. However, once a grain has acquired its red iron-rich clay coating, it will usually retain sufficient of it to impart a reddish translucent hue. When such dunes are blown into a river or into a lake and subjected there to rolling and wave action, the grains are rapidly stripped of their red coatings. They may emerge on the downwind banks or beaches as clean white sands with only occasional traces of red staining.

Following this line of evidence, the origin of the whitish sands in the large irregular lobes that transgress from South Australia into Victoria may be a function of the following factors.

Firstly, if the sands consisted originally of pure quartz there may have been insufficient clay to form the cutan in which haematitic iron is located. But it may be argued that given sufficient time all quartz dunes would eventually turn red, an argument that is not entirely supported by the persistence of pale colours in dunes of Saharan Africa and Saudi Arabia.

Secondly, such dunes lacking clay and carbonate are most susceptible to erosion and re-mobilization. They have probably been active more frequently and for longer periods than other dunes in the area. Thus they have never been stable for sufficient time to develop distinctive pedogenic horizons.

In the area west of Outer Arumpo Lake regular linear dunes pass progressively into steep, less regular siliceous forms. Here there appears to have been an evolution through stable linear forms, with sufficient clay to produce effective pedogenesis, to totally mobilized forms from which the clay has been removed during deflation. Unlike the Victorian irregular dunes, a strong reddish colour is characteristic of the irregular dunes between the Darling River and Willandra lakes. This represents an inherited feature of past more stable conditions. Conversely the absence of rubefaction in the irregular lobes of Victoria may reflect a combination of initially low clay content and periods of stability too brief to permit pedogenic rubefaction to take place.

Aeolian Clay

The problem concerning the origin of the clay plains has already been referred to. Lying on the downwind side of dunefields they almost certainly contain a significant component of wind-blown clay and fine sand derived during the long period available for the accession of airborne dust. Although mapped previously as 'parna' (Rowan & Downes 1963) the magnitude of dust accession in the composition of the plains remains unconfirmed.

Some indication of the depth and characteristics of aeolian clays in this region can be ascertained from examination of sediments that cap the Gredgwin Ridge. Its upper level lies well above the influence of fluvial or lacustrine deposition. Within the quarry studied by Macumber (1969a) upper Tertiary silicified and ferruginous sandstone is

overlain by 2 m of reddish sandy clay which we have examined in thin-section. Assuming relief of the block dates from soon after regression of the Tertiary sea, the upper clay-rich unit can only have been derived either by weathering of underlying sediment or from airborne dust from areas further west. In a profile from this quarry the mineralogic and weathering characteristics of the upper 1.5 m demonstrates that it is genetically distinct from the underlying sands. Moreover the upper clay-rich and basal marine sand units are separated from each other by a major weathering disconformity. At the contact, translocation of iron and silica has produced extensive ferric iron concretions and nodules associated with secondary opaline silica.

Therefore the surficial clay cover represents a later accumulation and is best explained by aeolian deposition of fine grained material from suspension (*parna* of Butler 1956) equivalent to the various aeolian episodes recognised within the linear dunes to the west. The clays contain a high percentage of silt-size quartz with characteristic ferric iron-rich kaolinitic cutans similar to Wüstenquarz grains derived from desert dusts, a feature that reinforces evidence for an aeolian origin.

Assuming that the dust component once lodged on the Gredgwin surface was not removed by later deflation, the evidence points to deposition of up to 2 m of fine grained sediment equivalent in time to the growth of the linear dunes. However, on the clay plains to the west of the Gredgwin and Cannie ridges fine grained deposits often exceed 2 m, suggesting that other depositional processes in addition to aeolian activity have been involved in their origin.

Land-use and Recreational Activities

Ample statements are to be found elsewhere of the impact of Man in this landscape, where a delicate balance exists between its ecosystems, landform stability, hydrology and climate. A slight disturbance in one is sufficient to cause drastic and perhaps irreversible changes in the other. The effects of vegetation clearance and irrigation, with consequent and widespread increases in salinization, are just some examples. It is not our intention to summarize the various practices of dry land and irrigation farming that have been developed within this region. However, in addition to the predominantly agricultural economy there is one aspect of land-use whose importance and impact will accelerate dramatically in future years. This concerns tourist, recreational and educational activities.

The Willandra Lakes lie near the centre of a circle, on the circumference of which lie the great urban centres of Adelaide, Melbourne and Sydney. Landholders in the Willandra area, within this once forgotten quarter of western New South Wales, are now being awakened to the reality that half Australia's population lives within just one day's drive of them. The invasion of sightseers, tourists, school tours and other elements more destructive to fauna and flora has increased dramatically in recent years. Already the State authorities have recognized the necessity to cater for these activities, the intensity of which will increase exponentially as urbanized society becomes increasingly more disenchanted with its environment. The existence of National Parks at Menindee (Kinchega), Hattah Lakes and Wyperfeld are tangible expressions of the States' concerns. However, given the marginal economic viability of both dry land grazing over large areas in the Western Division of New South Wales and similar reservations about the value of irrigation with its irremedial side effects on both sides of the border, serious consideration should be given to declaring large tracts both north and south of the Murray as protected wilderness areas. In Victoria, Lake Tyrrell, the largest salt lake in the state, together with sections of the Sunset and Big Deserts should be considered. In New South Wales consideration for protection of the Willandra Lakes is already in progress. Additional areas might include large tracts of relatively undisturbed mallee dunefields including part of the permanent drainage of either the Darling River or the Darling Anabranch near Travellers Lake; Lake Victoria with its proven scientific potential might also be so protected.

Whilst we acknowledge the financial problems this involves for State authorities and the possible inconvenience to present landholders, the long term needs of the Australian community demand that representative portions of this region with its scientific, aesthetic and recreational value be protected for future generations.

CONCLUSIONS

The geomorphic map of the Mallee region demonstrates a variety of aeolian, lacustrine and fluvial landforms that are distinctively 'Australian' in character. The record of past environments extends back to late Tertiary time when the NW.-SE. trending ridges were built as successive strandlines during final retreat of the Tertiary sea. Today the ridges often control the course of drainage lines and the location of terminal lakes.

The area is dominated by a variety of dune forms almost all of which are now vegetated. Thus the subdued linear dunes, the irregular lobes of large sub-parabolic dunes and the lake-shore transverse lunettes preserve the legacy of Quaternary environments when aeolian activity was much greater than it is today. Similarly the two varieties of lakes, the elliptical lunette lakes and irregular gypseous groundwater lakes, in their shoreline features and associated aeolian sediments, reflect alternating periods when both groundwater and surface water supplies were sometimes in excess of, and at other times, less than those of today's regime. In this respect the Mallee region will continue to prove a fruitful area for studies of Quaternary environments, a context that will continue to tell us more of early Man and of changing flora and fauna in this continent.

Earlier studies established that whilst several phases of lunette development are evident on many lake basins throughout the region, the last lunettes were built about 18,000 to 16,000 B.P., simultaneously with the maximum extent of global glaciation. At the same time both linear and transgressive sub-parabolic dunes were reactivated.

The mechanism by which regular, subdued linear dunes were formed, with high clay and carbonate content, involved deflation of sediments from adjacent flanks and swales. The dunes accumulated layer by layer over the pre-existing topography. They did not form mobile sand-slip faces nor did the forms migrate significantly downwind. The presence within their sediments of pelletal clay aggregates suggests a mechanism of formation resembling that documented for transverse clay-rich lunettes. In this process, salinization of swales following the long period of high watertables that existed before 25,000 B.P. may have played an important part in destroying vegetation and in breaking up calcareous clays and sands by efflouresence of salts; the pellets and sands then formed blanket deposits on adjacent dunes. The shapes preserved today closely resemble the original depositional form; they are not degraded remnants of once larger features.

Variations in form and colour of dunes may be a primary function of the parent material, particularly the content of clay. Without clay present, the process of rubefaction is inhibited and may even be prevented if the dune soils do not remain stable long enough to develop well defined profile differentiation. Increasing quantities of clay and carbonate effectively fix the dune form, ensuring its relative stability.

The contribution of windblown dusts forms an important constituent of the plains east of the main dunefields; some 2 m of fine grained sediment on the Gredgwin Ridge has originated in this way. An equivalent fine-grained component would have been contributed to the surrounding clay plains.

Finally, the area presents many striking examples of the influence of past hydrologic changes on landforms and ecosystems delicately adjusted to the controlling climatic regime. Throughout the past 100 years of intensive European settlement many changes have been initiated, some of which may prove irreversible. Careful planning is necessary to ensure the long-term protection of this region, the future value of which may involve land-use other than the present pastoral and agricultural activities. It is already proving to be one of growing importance for those who live in the sprawling urban centres of Adelaide, Melbourne and Sydney, centres that lie less than one day's drive from this most attractive semi-arid corner of southeastern Australia.

ACKNOWLEDGMENTS

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EXPLANATION OF PLATES

Plate 2

1. Vertical aerial photograph (a in Fig. 3) showing junction between cleared, cultivated linear dunefield in north and dark field of vegetated irregular to sub-parabolic dunes in the south. Compare dune forms with perspective diagrams, Figs. 5 and 6. Pale strip through irregular dunes in south-west represents a fire scar.

2. Vertical aerial photograph of the margin of Big Desert (b in Fig. 3). Dark vegetated siliceous dunes in north pass into subdued linear forms in the south developed on crests of NNW.-SSW. trending ridges one of which is marked by a dark strip of mallee woodland. A small lake basin and lunette have developed in the inter-ridge corridor.

North is at the top. Scale approx. 1:85,000. Crown copyright photographs by courtesy Director, Division of National Mapping, Canberra.

Plate 3

1. Vertical aerial photography of southern part of Outer Arumpo-Chibnalwood Lakes system set within the linear dunefield (d in Fig. 3). Broken line marks the shoreline of large freshwater lake (Outer Arumpo) with a pale lunette crest on the east. The outline of the inner saline deflation basins with steep gullied lunette ridges is defined by pale scalds.

2. Vertical aerial photograph of gypseous groundwater basin on the southern margin of Sunset Desert (c in Fig. 3). Irregular vegetated dunes in the north-west pass south into regular linear forms in the bottom left hand corner. In the centre a field of steep and high longitudinal siliceous dunes represent a form often found near the transitional zone between irregular and regular, subdued forms. The linear dunes have transgressed to the east across saline gypseous flats. Note their tendency to form Y-junctions. White areas represent small salt encrusted groundwater discharge sites within a formerly larger lake.

North is at top of page. Scale approx. 1:85,000. Crown copyright photographs by courtesy Director, Division of National Mapping, Canberra.

Plate 4

1. Vertical aerial photograph from Willandra Lakes region (e in Fig. 3) illustrating a vegetated sand plain with poorly defined dune ridges in the west. The plain is truncated on the east by the cliffed westerly margin of Lake Mulurulu.

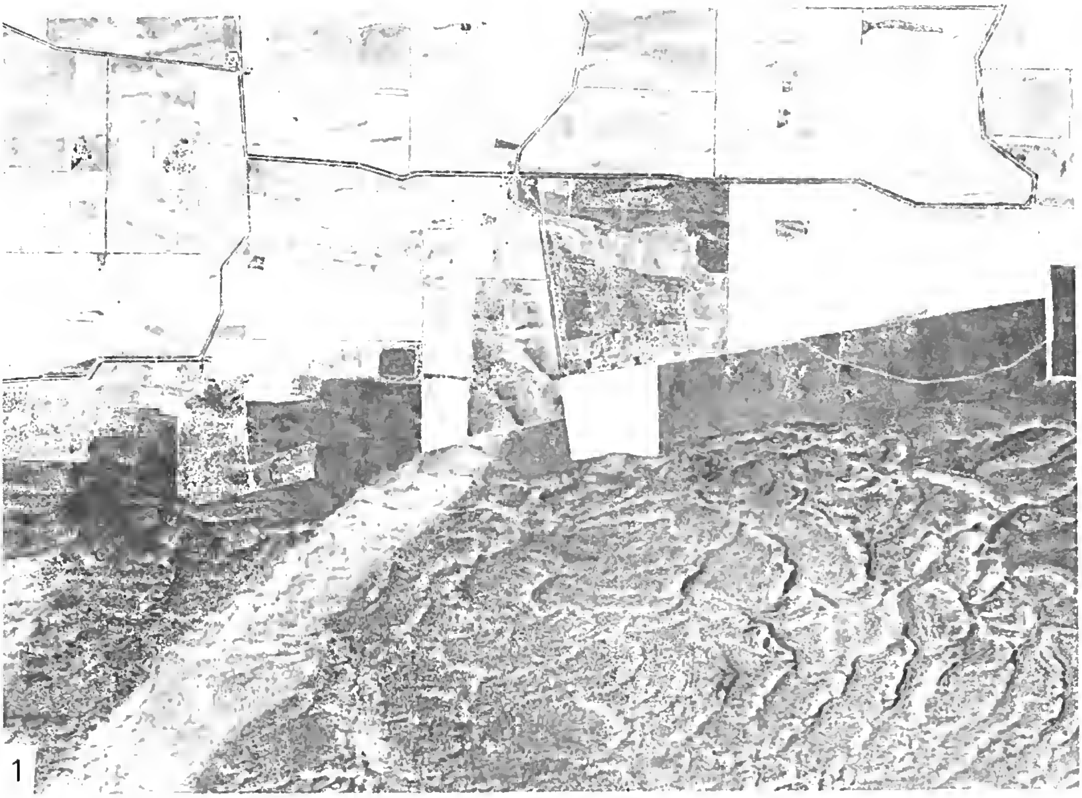
2. Vertical aerial photograph of area east of Rainbow, Victoria (f in Fig. 3), showing set of NNW ridges with sandy crests. Clay-rich swales are overlain by a thin surface sand cover giving rise to the unit mapped as 'clay plain with sand cover'.

North is to the top. Scale approx. 1:85,000. Crown copyright photographs by courtesy Director, Division of National Mapping, Canberra.

Plate 5

Vertical aerial photograph of the Murray River at Lake Victoria (g in Fig. 3) with river flowing in tract of low level alluvium with extensive scroll bars, oxbow swamps and distributary channels of Rufus River and Frenchmans Creek. In the south a belt of high level alluvium, with a surface patchwork of whitish scalds, stands as a terrace above younger alluvial deposits. In the north, the Lake Victoria basin is bounded on the west by linear dunefields and on the east by a sandy lunette (see Gill 1973).

North is to top of photograph. Scale approx. 1:85,000. Crown copyright photograph by courtesy, Director, Division of National Mapping, Canberra.



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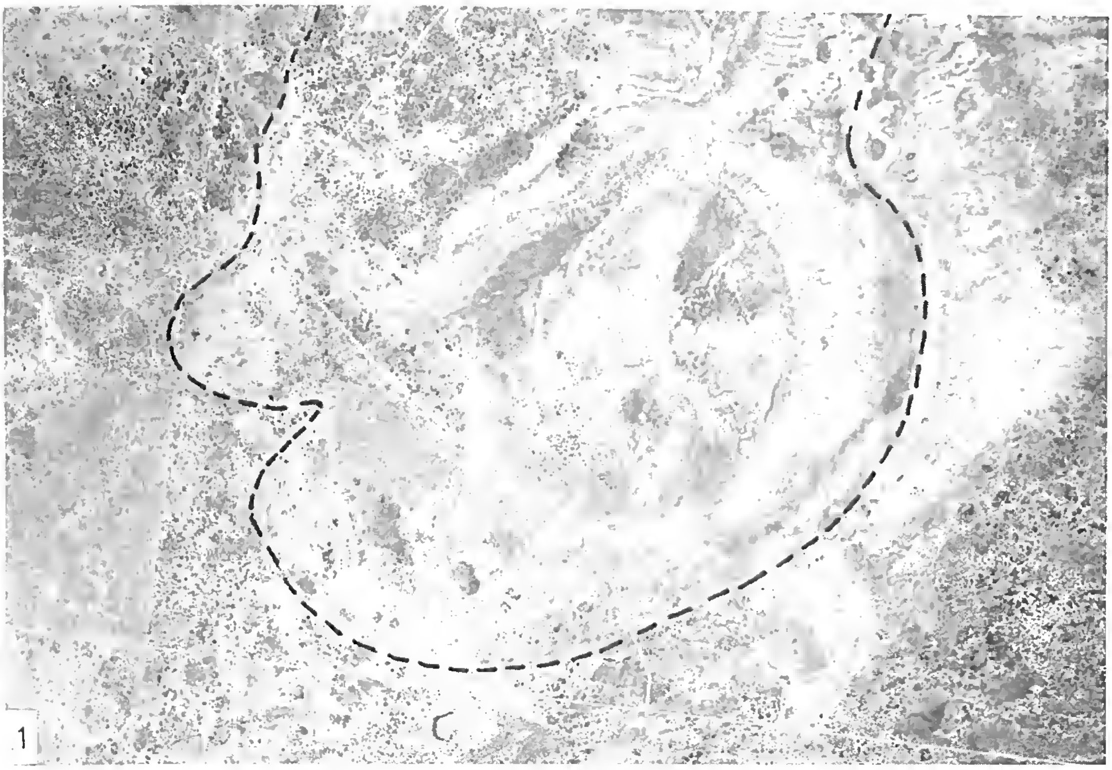

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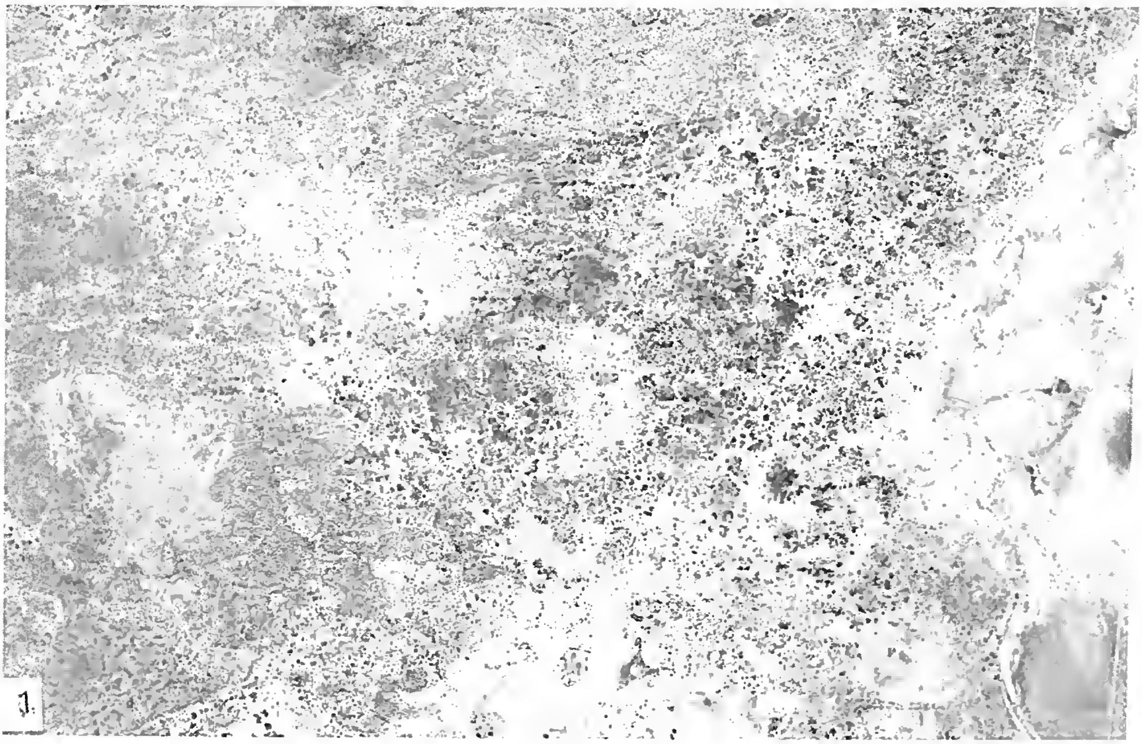

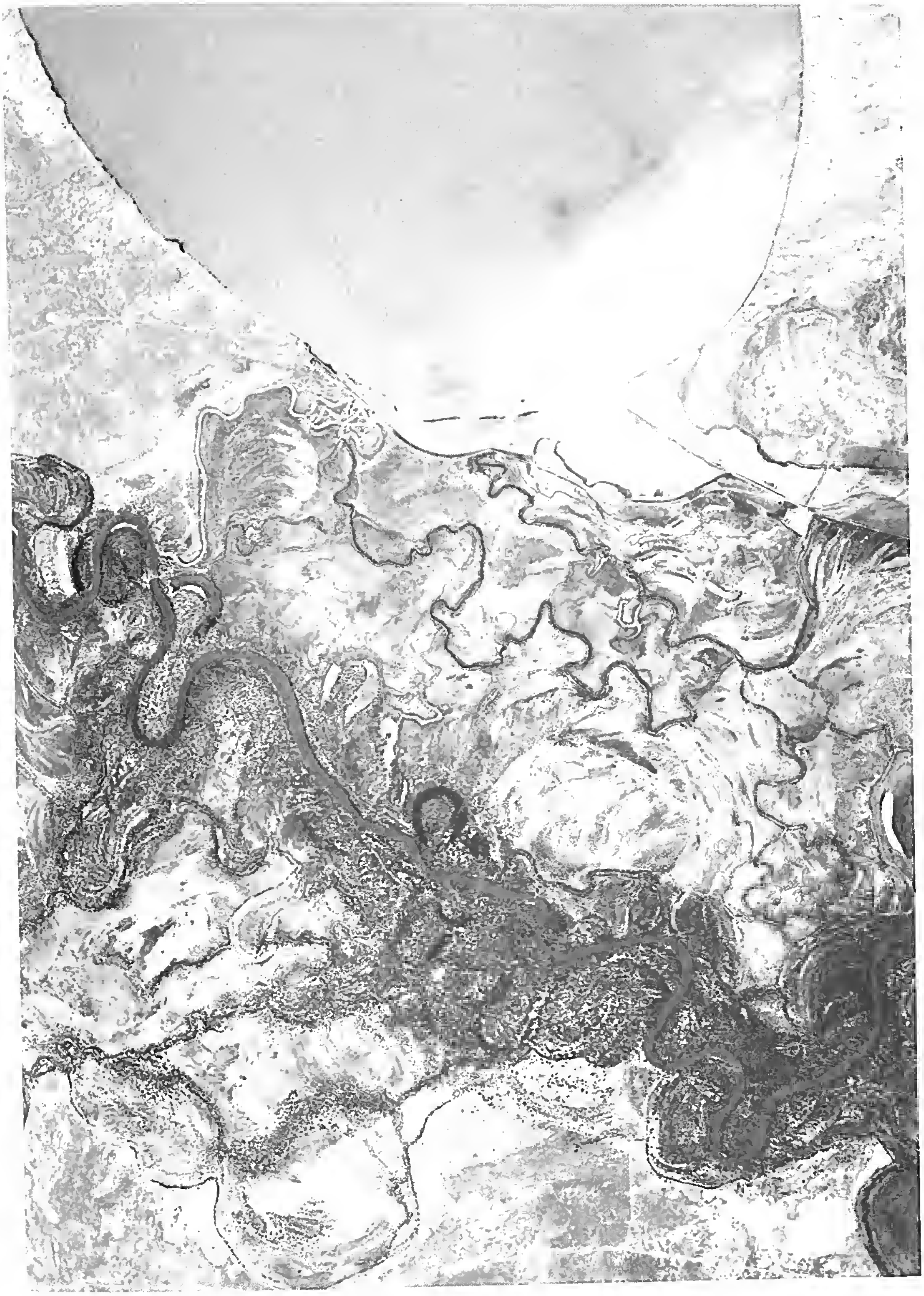

3

AGE AND ORIGIN OF THE MURRAY RIVER AND GORGE IN SOUTH AUSTRALIA

By C. R. TWIDALE, J. M. LINDSAY[2] AND J. A. BOURNE[1]

ABSTRACT: The course of the Murray River in South Australia has been determined largely by geological structure. Following mid-Tertiary and early Pliocene marine sedimentation in the western Murray Basin, the ancestral Mt Lofty Ranges were rejuvenated in the middle Pliocene. A precursor of the Murray River developed a course near the ranges, mainly north-south but already branching eastwards to Overland Corner. This valley system was drowned by a late Pliocene marine transgression which deposited estuarine Norwest Bend Formation.

In the early to middle Pleistocene, the Pinnaroo Block emerged as a positive feature. 'Lake Bungunnia', which was formed at least partly by tectonic blockage, drowned the proto-Murray and occupied lowlands to the north, east and west of the Block.

Glacio-eustatic low sea levels of 100-150 m below present MSL in the middle and late Pleistocene, led to progressive headward recession and incision of the Murray Gorge, and to the cutting of the Murray submarine canyons across the continental slope.

The main valley-fill of Monoman and Coonambidgal Formations formed by aggradation to rising base-level during the post-glacial (Flandarian) rise in sea level.

INTRODUCTION

Problems posed by the age and origin of the Murray River in South Australia have engaged the attention of geologists for almost a century, since Tate (1885) proposed an explanation for the gorge tract between Overland Corner and Wellington.

Both in gross and in detail the South Australian sector of the river is notable for its seemingly erratic course. It runs in an overall westerly direction between the Victorian border and North West Bend, whence it turns through ninety degrees to flow southwards to the Southern Ocean. Several abrupt local changes of direction are superimposed upon this regional pattern, those at South (Great Pyap) Bend, Overland Corner, and Chucka Bend being the most prominent (Fig. 1).

Between the State Border and Overland Corner (the section 1 of Tate 1885) the Murray flows in an alluvial valley, which is characterised by scroll plains and abandoned river loops preserved as arcuate lagoons and swamps, and which is subject to seasonal flooding (Pl. 6). This modern flood plain is contained within older alluvial and lacustrine sediments of Late Cainozoic age (Fig. 2A).

At Overland Corner, the character of the river valley changes dramatically, for between that point and Wellington (Tate's section 2) the Murray flows in a comparatively narrow, deep and steep-sided trench or gorge (Figs. 2B, C, Pl. 7 & 8).

Though it varies from site to site the gorge is typically 30-40 m deep from the cliff top to the valley floor, and 600-1400 m wide, so that this gorge, like most others, is much wider than it is deep (Johnson 1932). The form of the bounding cliff varies systematically with its position vis à vis the river, being vertical where the winding river, which usually occupies only a small part of the gorge floor, impinges on the valley sides, and more gentle, even graded, on the inside of the river curves (Tate 1885, Twidale 1968 pp. 171-173).

The gorge is not, however, a simple feature, for the steep cliffs in many places give way to an open upper section so that an overall valley-in-valley form is displayed. The upper valley is mostly due to the greater erosion of such weaker lithological units as the Blanchetown Clay (Pl. 7, above), but in places may relate to remnants of a valley older than the gorge proper, as for example near Walker Flat.

[1] Department of Geography, The University of Adelaide, South Australia, 5000.
[2] Geological Survey of South Australia, Box 151 Eastwood, South Australia, 5063. Published with the permission of the Director-General of Mines and Energy.

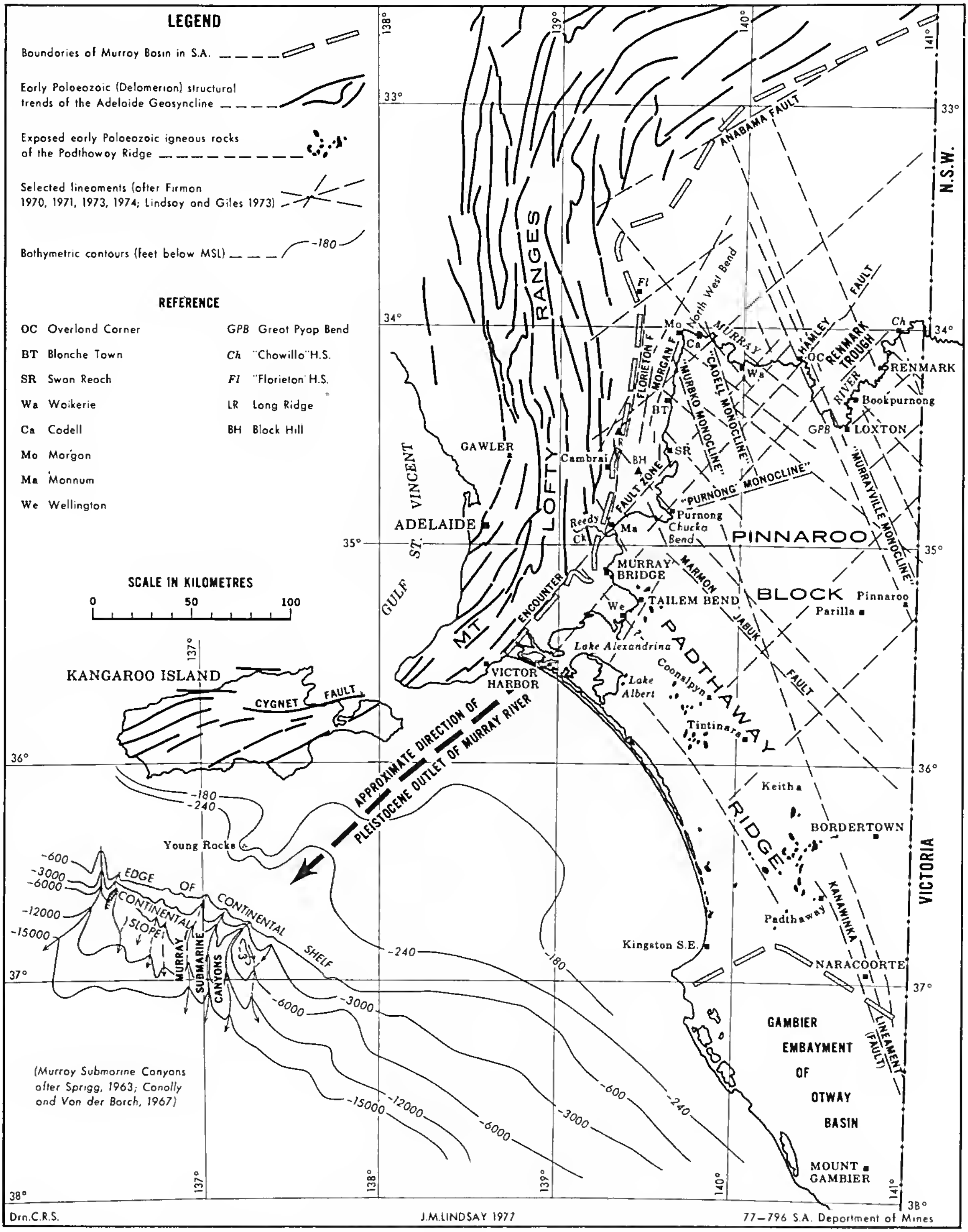

FIG. 1 — Structural elements influencing the course of the Murray River in South Australia.

STRUCTURAL CONTROL

Several writers have suggested that in broad view the course of the Murray is controlled by structural factors. Thus Hills (1956, p. 2) stated that far from being capricious, 'tectonic significance must be attached to every stretch of the River Murray, and that from the trends alone a clear indication of structure — the nature requiring to be investigated in each case — is provided.'

Regional Structure: The overall direction of the Murray from Morgan to the Murray mouth, and indeed its Pleistocene extension across the continental shelf, was controlled by the south to southwest Delamerian structural trends in the Late Precambrian to Early Palaeozoic rocks which form extensive outcrops in the Mt Lofty Ranges and which frame the western Murray Basin (Fig. 1: Delamerian trends after State Geological Map, 1:1,000,000, S.A. Dept. Mines & Energy, in prep.).

The sub-meridional course of the Murray south of Morgan lies close to the western border of the Murray Basin where the plains are lowest (Fig. 3). This is in part due to the late Cainozoic regional sagging or subsidence of this western area that accompanied continued uplift of the Mt Lofty horst block at that time (Sprigg 1952, p. 116). Yet the river does not run close to the eastern piedmont of the Mt Lofty Ranges, and is not diverted by those uplands as was suggested by Howchin (1929). A fault block of crystalline rocks which is part of the structural horst and yet is marginal to the topographic upland, underlies the western edge of the Murray Basin. Uplifted along the Florieton and Morgan faults (Figs. 1, 4) the block forms an area of high ground, and is here named the Cambrai Block (cf. 'Cambrai Plateau' of Firman 1964, 1973). The Cainozoic cover is relatively thin (less than 100 m) though of variable thickness, so that the basement rocks are nowhere far beneath the surface and many small outcrops of crystalline rocks occur, e.g. norite at Black Hill, granite at Long Ridge. The Murray River flows in the

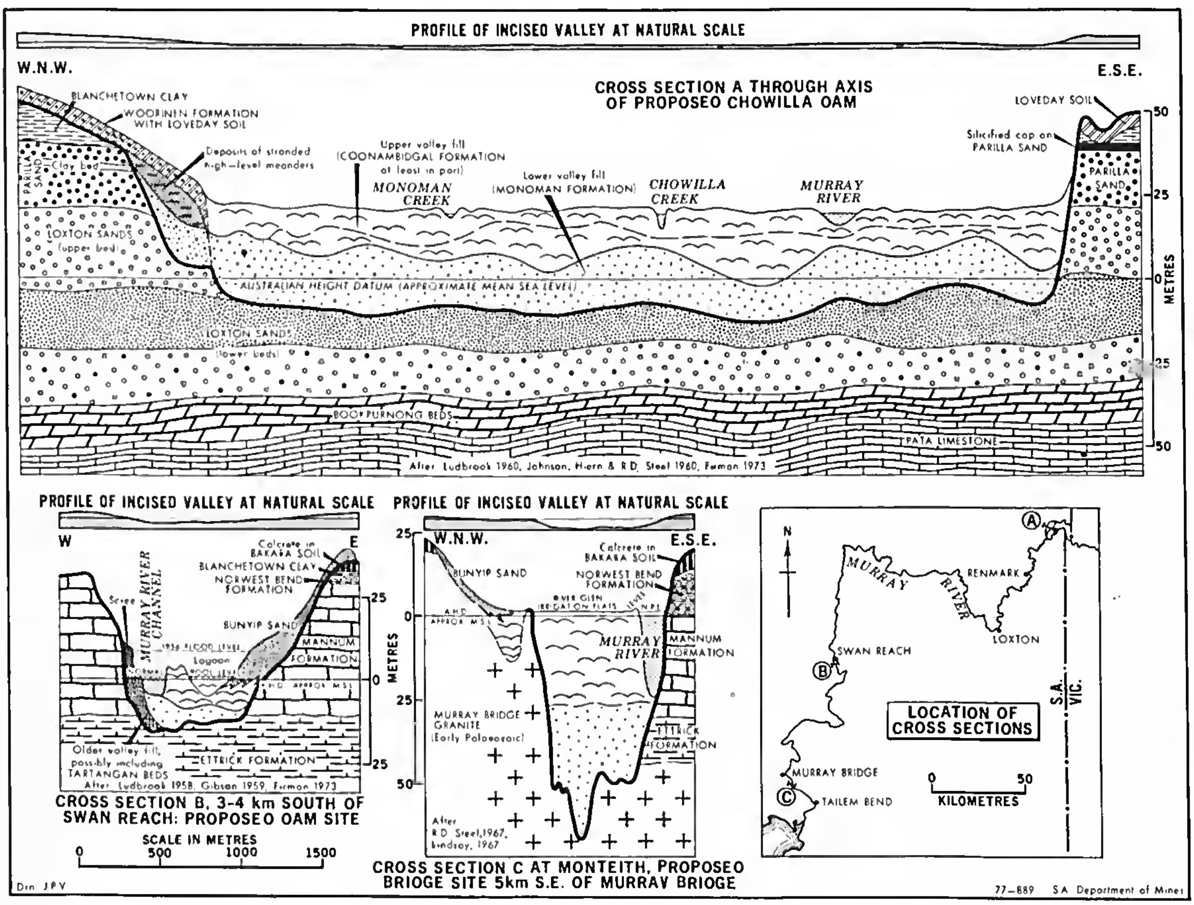

FIG. 2 — Cross sections through Murray River valley near Chowilla (A), Swan Reach (B) and Murray Bridge (C).

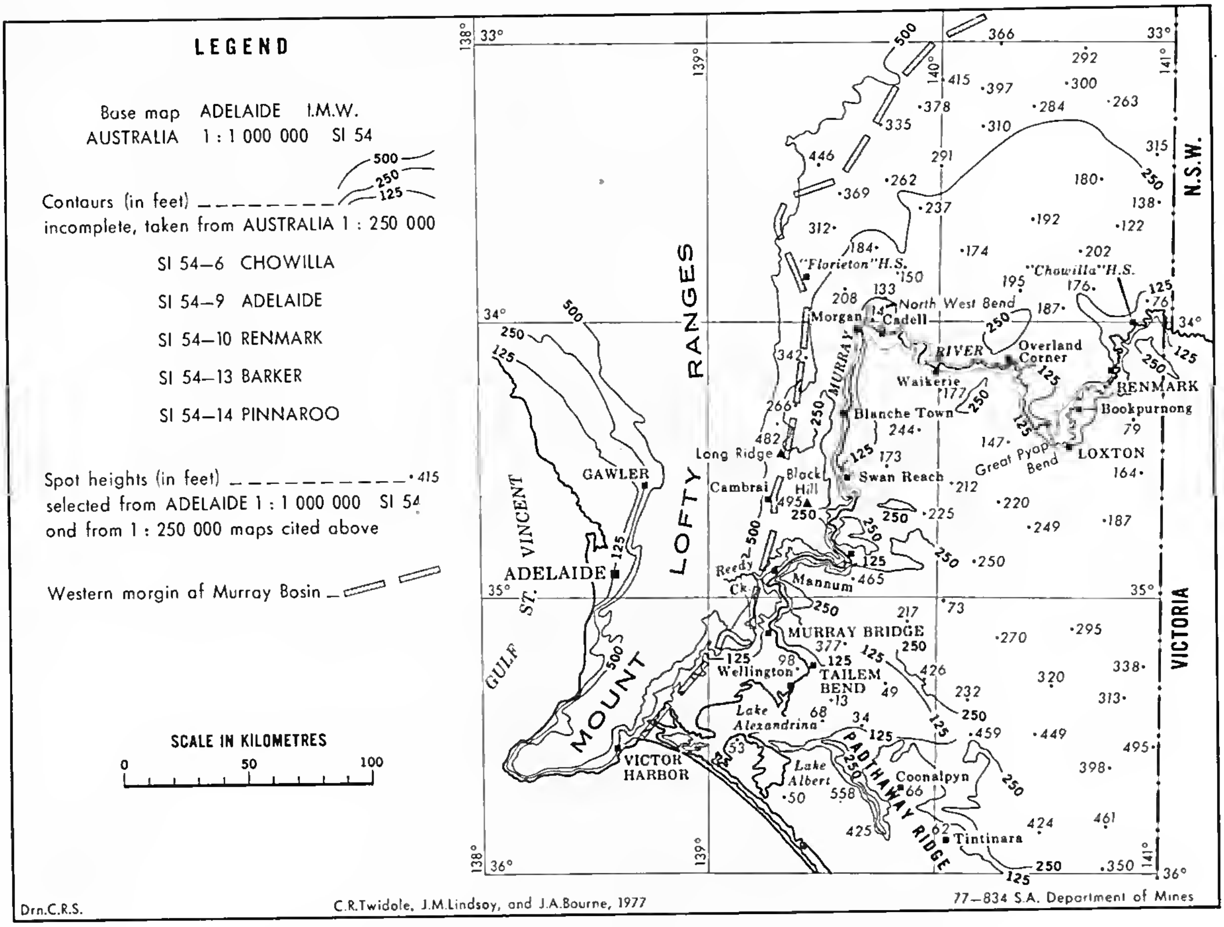

FIG. 3 — Topographic map of Murray Basin in South Australia.

depression between the east-facing fault scarps of the Cambrai Block and the gentle western decline that makes up the greater part of the Basin surface (Fig. 3).

Resurgent Tectonics: The transmission of basement structures to the overlying, essentially undeformed, sedimentary sequence is known as resurgent tectonics (Hills 1963, p. 333). Fractures in the crystalline rocks that underlie and delineate the Murray Basin form part of a continent-wide pattern of lineaments (Hills 1946, 1956, 1961). Recurrent joggling of the blocks so defined has caused similar fracture patterns to evolve in the flat-lying Basin sediments (Hills 1956, 1961, Firman 1970, 1971a, 1973, 1974, Lindsay & Giles 1973). These steeply dipping faults and joints have profoundly affected the course of the Murray.

Thus the major westerly diversion of the river between Purnong and Wellington, involving Chucka Bend and Tailem Bend, is related to the renewed uplift of the Marmon Jabuk structure (Fig. 1). In the present lakes area (section 3 of Tate 1885) the river is diverted northwesterly around the Padthaway Ridge or Horst. Again, the southerly course of the river between Morgan and Purnong runs in general parallelism, though it is not closely coincident, with the Morgan-Florieton fault zone.

Even outside the confines of the gorge, in the alluvial upper reaches of the Murray valley in South Australia, basement structures are reflected in the course of the river. The southwesterly trend of the river from Chowilla to Loxton follows the edge of the Renmark Trough (Fig. 1) which developed in the Middle to Late Palaeozoic (Thornton 1974). The Trough, the associated Hamley Fault, and the Encounter Fault Zone had Palaeozoic or even older origins, but were reactivated in the Cainozoic to produce gentle warping and fracturing in the Permian, Cretaceous and Tertiary sedimentary cover overlying displaced basement blocks. This appears to have had a subtle but decisive influence on the course of the river in this sector. Again, the northwesterly trend of the Murray from Loxton to Overland Corner

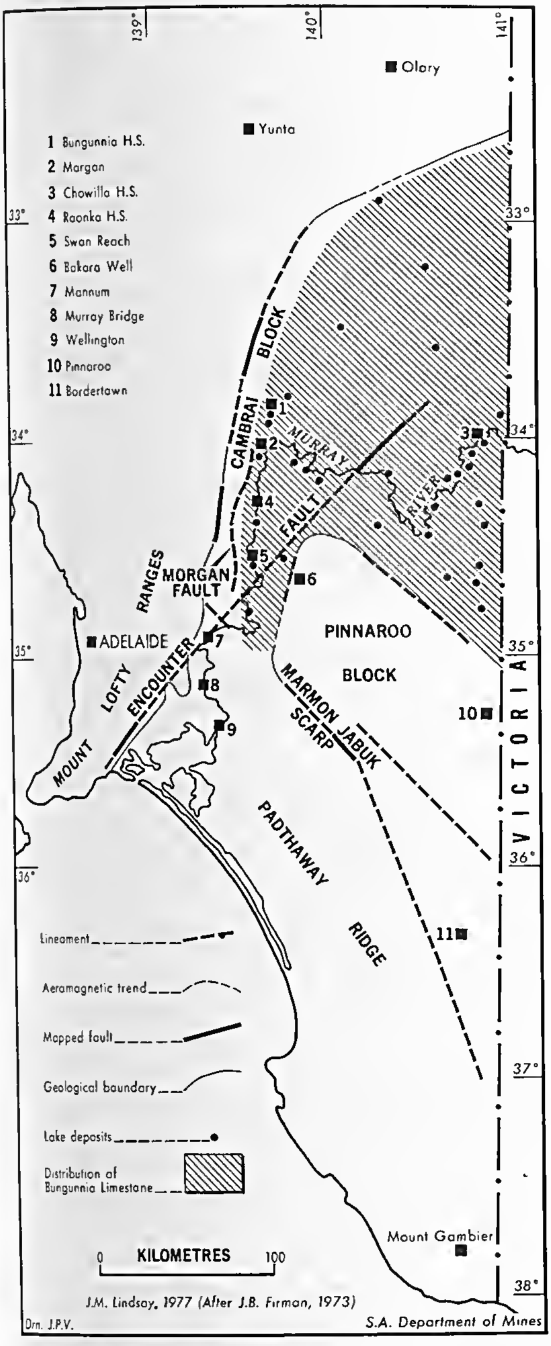

FIG. 4 — Extent of early to middle Pleistocene 'Lake Bungunnia' in South Australia.

follows the Murrayville Monocline (Spence 1958, O'Driscoll 1960, Lindsay & Giles 1973).

Major Joints: Within these broad regional trends the river and its valley wind about in what are at first sight hydraulic curves but which on closer inspection are controlled in considerable measure, as O'Driscoll (1960) pointed out, by NW.-SE. and NE.-SW. trending major joints developed in the Miocene limestones, possibly as a result of shearing along major basement structures (Fig. 1).

Thus the course of the river has been influenced at various scales by the structure of the basin sediments which in turn reflect structure in the underlying crystalline basement.

DEVELOPMENT OF THE MURRAY RIVER

Table 1 summarises various stages of development of the Murray River and its precursors in geological and stratigraphic perspective, which is mainly local, but includes a somewhat speculative correlation with major worldwide Quaternary glacio-eustatic events. The time scale is after Van Eysinga (1975), Tarling & Mitchell (1976), and La Brecque *et al.* (1977).

TERTIARY

Earlier Tertiary Events in the Murray Basin: Tertiary sedimentation in the western Murray Basin was initiated by uplift of the ancestral Mt Lofty Ranges along rejuvenated Delamerian fault-trends, probably in the early Palaeocene, and thus preceding the separation and drifting of the Australian Plate from Antarctica (Weissel & Hayes 1972, Deighton *et al.* 1976). The oldest Tertiary sediments in the area are palynologically dated middle Palaeocene and are of fluvio-lacustrine origin, but unrelated to the present Murray River. In a borehole at Waikerie, quartz sands, gravels, and carbonaceous clays of this age were intersected at 305-332 m (Harris, in Lindsay & Bonnett 1973). In the Loxton 'Company Bore', further southeastwards into the Basin, and away from the marginal ranges, carbonaceous silts at 487-515 m comprising the basal part of stratotype Renmark Beds, are of the same age (Harris 1966, 1970).

Sagging of the trailing margin of the northward drifting continent led to progressive marine transgression into southern Australian sedimentary basins from the middle Eocene onwards. The sea had entered the Murray Basin in South Australia by the late Eocene, and deposition of fossiliferous sands, marls and limestones on this epicontinental marine shelf continued, at least in the deeper parts of the Basin, until the middle Miocene (Pata Limestone). Early to middle Miocene sandy limestones of Mannum Formation and Morgan Limestone are the characteristic cliff-forming rocks of the River Murray gorge-tract (Pl. 7 & Pl. 8 above) between Overland Corner and Tailem Bend (Ludbrook 1961, Giles 1972, Lindsay & Giles 1973).

In the Murray Basin, as in the other South Australian coastal Tertiary basins, this cycle of

TABLE 1

DEVELOPMENT OF THE MURRAY BASIN AND MURRAY RIVER IN SOUTH AUSTRALIA — STRATIGRAPHIC TABLE.

AGE (Years)	ERA	PERIOD	EPOCH		STRATIGRAPHIC UNITS	EVENTS
	CAINOZOIC	QUATERNARY	RECENT (HOLOCENE)	LATE	COONAMBIDGAL FORMATION	Fluvial aggradation; "upper valley fill", with varied fluvial landforms.
					BUNYIP SAND; Tortongon beds	
1×10⁴ LOG SCALE ↓				EARLY	MONOMAN FORMATION	Post-glacial rise of sea level (Flandrian Transgression); fluvial aggradation: "lower valley fill"
			PLEISTOCENE	LATE	LOVEDAY PEDODERM; WOORINEN FORMATION	Last glacial maximum; climatic stage 2; glacio-eustatic low sea level; major incision of Murray River "gorge" and offshore Murray Submarine Canyons; regional aridity; east—west sand dunes of Woorinen Formation; loess; soil—carbonate accumulation (Loveday Pedoderm). Onset of last major refrigeration
					POORAKA FORMATION	Lake Mungo and Keilor Man. Interglacial climatic stage 3.
					BAKARA SURFACE	Glacial maximum; climatic stage 4 glacio-eustatic low sea level. ? formation of pre—Woorinen deposits of high—level meanders. ? formation of "cliff — side channels"
1×10⁵					CALCRETES IN BAKARA PEDODERM; Glanville Fm. *Anadara*; Upper Member Bridgewater Fm.	Interglacial climatic stage 5. Last Interglacial High Sea Level. Glacial climatic stage 6 glacio-eustatic low sea level. Interglacial climatic stage 7. Glacial climatic stage 8. Interglacial climatic stage 9. Glacial climatic stage 10. Glacial climatic stage 12. Phases of glacio—eustatic low sea level; ? incision of Murray River precursor and offshore Murray River Submarine Canyons; loess; soil—carbonate accumulation. Uplift of Cambrai Block along Morgan Fault.
				MIDDLE	RIPON SURFACE; RIPON CALCRETE	Major glacial climatic stages 16—18; glacio-eustatic low sea level; loess; soil—carbonate; ? incision. Brunhes/Matuyama palaeomagnetic reversal.
1×10⁶				EARLY	BUNGUNNIA LST.; BLANCHETOWN CLAY; CHOWILLA SAND; COOMANDOOK FM.; Lower Member Bridgewater Fm.	Pre-Ripon incision of high-level channels of Murray precursor. "LAKE BUNGUNNIA" fluvio—lacustrine deposition. KAROONDA SURFACE; KAROONDA PEDODERM; silicification. Appearance of Pinnaroo Block. Withdrawal of sea to Padthaway Ridge area (Coomandook Formation).
2		TERTIARY	PLIOCENE	LATE	NORWEST BEND FM. (estuarine); PARILLA SAND (fluvio—lacustrine)	TIMBOON PEDODERM; ferruginisation. Marine transgression up valley of Murray River precursor. Development of precursor of Murray River. Rejuvenation of ancestral Mt. Lofty Ranges. Withdrawal of "Loxton Sands" sea.
3, 4, 5				EARLY	LOXTON SANDS; BOOKPURNONG BEDS	Commencement of Pliocene marine transgression.
6, 7, 8, 9, 1×10⁷			MIOCENE	LATE		Erosion; gentle warping; minor faulting.
				MID.	PATA LIMESTONE; MORGAN LIMESTONE	(?) Glacio-eustatic and epeirogenic withdrawal of sea from Murray Basin.
2				EARLY	MANNUM FORMATION	Deposition of mid-Tertiary marine sequence
3			OLIGOCENE		ETTRICK FORMATION	
4			EOCENE	L, M	BUCCLEUCH BEDS	Commencement of Tertiary marine transgression in western Murray Basin.
5				E	RENMARK BEDS	Commencement of northerly drift of Australian Plate from Antarctic Plate. Commencement of Tertiary fluvial sedimentation, western Murray Basin. Rejuvenation of ancestral Mt. Lofty Ranges.
6, 7, 8, 9			PALAEOCENE			
1×10⁸	MESOZOIC	CRETACEOUS				Early Cretaceous marine to non-marine deposition in Cretaceous infrabasins.
		J				Commencement of rifting phase of Australia-Antarctic break-up.
2		T				
3	PALAEOZOIC	P, C				Development of Renmark Trough. Early Permian glacial diamictites of the Renmark Trough.
4, 5		D, S, O, C				DELAMERIAN OROGENY: Formation of ancestral Mt. Lofty Ranges. Kanmantoo Trough
6, 7, 8, 9, 1×10⁹	PROTEROZOIC	ADELAIDEAN			Late Precambrian — Cambrian sedimentary rocks of the Adelaide Geosyncline	

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widespread marine sedimentation ended in the middle Miocene probably as a result of the combined effects of a glacio-eustatic fall in sea level associated with rapid growth of the Antarctic ice-cap (see Dorman 1966, Hollin 1962, 1969, Kennett *et al.* 1975, Shackleton & Kennett 1975, Savin *et al.* 1975) and epeirogenic uplift of the trailing continental margin.

Weathering, erosion, mild warping and block-faulting ensued through the middle to late Miocene. Lineaments formed then and subsequently in the mid-Tertiary limestones in relation to these faults, monoclines and joints, were later to influence greatly the course of the developing Murray River.

Pliocene Events: Early Pliocene transgressive marine and fossiliferous units comprise glauconitic fine sands and marls of the Bookpurnong Beds, and coarser quartz sands of lower Loxton Sands. These were succeeded by regressive fluvio-lacustrine upper Loxton Sands deposited as the 'Loxton' sea retreated (Fig. 2A). After a hiatus, estuarine oyster banks and fossiliferous sands of the Norwest Bend Formation were deposited as a result of a further warm-marine transgression in the late Pliocene (Ludbrook 1959, 1961, 1963). The distribution of Norwest Bend Formation was restricted to a comparatively narrow meridional depression extending to Morgan and northward, with already an easterly branch running through Waikerie to Overland Corner and Kingston-on-Murray (Fig. 5). Here, the Norwest Bend Formation grades into the non-marine, clayey quartzose Parilla Sand (Firman 1973, p. 15) which is typically developed on the Pinnaroo Block and in the Murray cliffs upstream from Bookpurnong. No doubt the Parilla Sand comprises, at least in part, the deposits of fluvio-lacustrine systems tributary to the Norwest Bend Formation estuary.

The Ancestral (Mid-Pliocene) Murray: The Norwest Bend Formation occupies a shallow north-south corridor or depression eroded in the Miocene limestones or the Loxton Sands. It delineates, and represents, the late Pliocene drowning of an initial valley cut by a south-flowing precursor of the Murray River in the topographic low which was caused by faulting and sagging near the western margin of the Murray Basin, as noted above (Sprigg loc. cit., Ludbrook 1961, p. 86).

What sort of river was this earliest Murray? Did it develop through headward erosion and gradually extend northward, or was it in effect an overflow from some inland lake? Whatever its origin some special circumstances must have obtained to account for the development of the ancestral

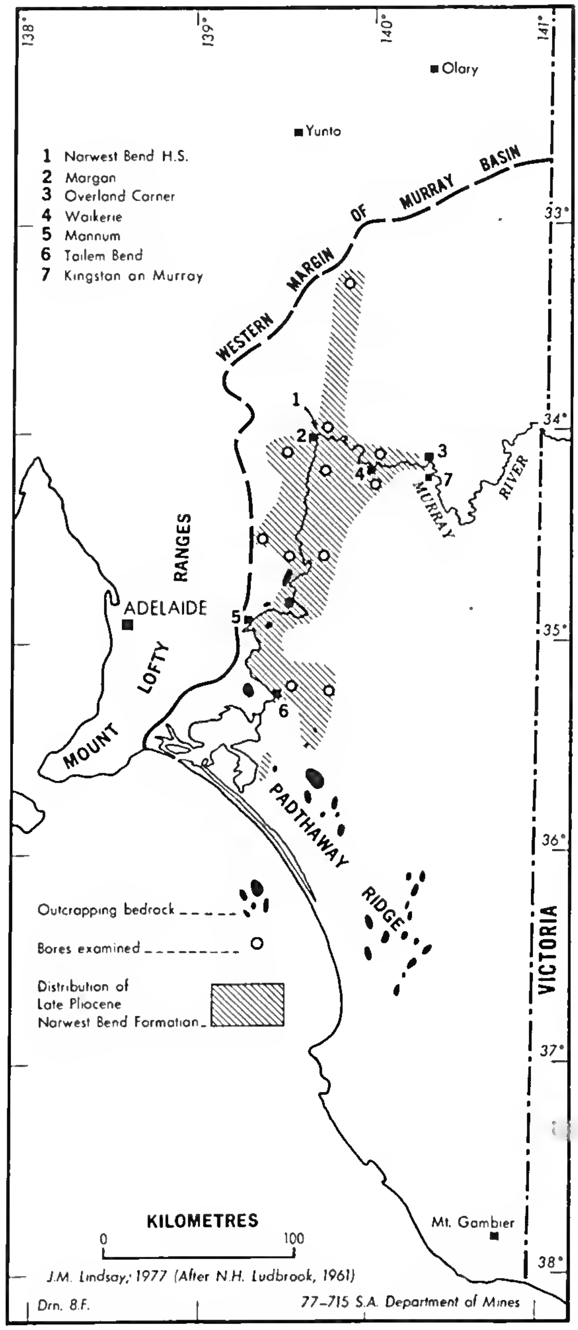


FIG. 5 — Distribution of Late Pliocene Norwest Bend Formation in Murray Basin in S.A.

Murray in the mid-Pliocene, enabling it to exploit the various structural weaknesses of the western Basin area, and erode a major valley.

The first advantage it had was that it was derived from, and fed by, the coalescence of streams emanating from the higher rainfall uplands to the west, the Mt Lofty Ranges. The shallowness of the

crystalline basement would have assisted in developing runoff. This heavier runoff alone would have allowed the western consequent to incise its bed more rapidly than its eastern competitors and to become the master stream of the network.

Second, and reinforcing the excavation of the ancestral Murray valley, there may have been overflow from a Late Tertiary fluvio-lacustrine system (? 'Lake Nawait', see David 1950, p. 614; Firman 1971a, 1973) which occupied much of western N.S.W. and northwestern Victoria (Tate 1885, Pels 1969, Gill 1973a, Lawrence & Abele 1976). It is not known whether that system was connected to the ancestral Murray considered here. However the simple form of the high-level valley of the latter argues against any significant contribution to its development by catastrophic overflow from an inland lake, for such overflow would result in floods and in the development of broad braided channels comparable to those associated with the 'jokulhlaup' of periglacial regions (see Thorarinsson 1939), with the Channelled Scablands of Washington, northwestern U.S.A. (Baker 1973), and indeed with most of the river channels of arid and semi-arid Australia, but especially the Channel Country (see e.g. Bonython & Mason 1953 opp. p. 324) in consequence of adjustment to flood conditions.

Thus the presence of the impermeable rock uplands to the west together with the adjacent tectonic basinal depression appear to be the principal factors leading to the dominant development of the ancestral Murray.

It was to this shallow valley, and later to the estuary occupying it, that the adjacent areas were eroded and graded to develop the rolling topography of the Murray Surface (Twidale & Bourne 1975). The high plains surface, modified by Quaternary events and deposits, is extensively represented in the western and southern parts of the Murray Basin in South Australia, but in the north is buried by Quaternary alluvial and lacustrine deposits such as the Blanchetown Clay and the Bungunnia Limestone.

Quaternary Events

General Remarks: The Murray Gorge is cut through the base of the Norwest Bend Formation of late Pliocene age, and is therefore essentially a Quaternary feature. Following withdrawal of marine influence from the Norwest Bend Formation estuary to the Padthaway Ridge, near the Plio-Pleistocene boundary, the ancestral Murray was re-established. Incision of its gorge was undoubtedly the result of Pleistocene glacio-eustatic lowering of sea level, particularly during the intensified cyclic development of continental ice sheets during the past 900,000 years (Shackleton & Opdyke 1973, 1976). Table 1 shows various glacial and interglacial climatic stages in a time-framework after these authors. The local stratigraphic succession follows Firman (1967, 1969, 1973) and

DESCRIPTION OF PLATES

Plate 6

Above — Oblique aerial view eastwards across Renmark, showing meandering course of upper Murray River, S.A., in broad alluvial valley with riverine swamps and abandoned river-loops. Murray plains with east-west dunes in the background. (Photo: S. Aust. E. & W. S. Dept.)

Below — Vertical air-photo, Renmark, showing complex river forms of the broad alluvial valley of the upper Murray River, S.A., including meanders, abandoned river-loops anabranches and riverine swamps. Top of photo is east. (Photo: S. Aust. E. & W. S. Dept.)

Plate 7

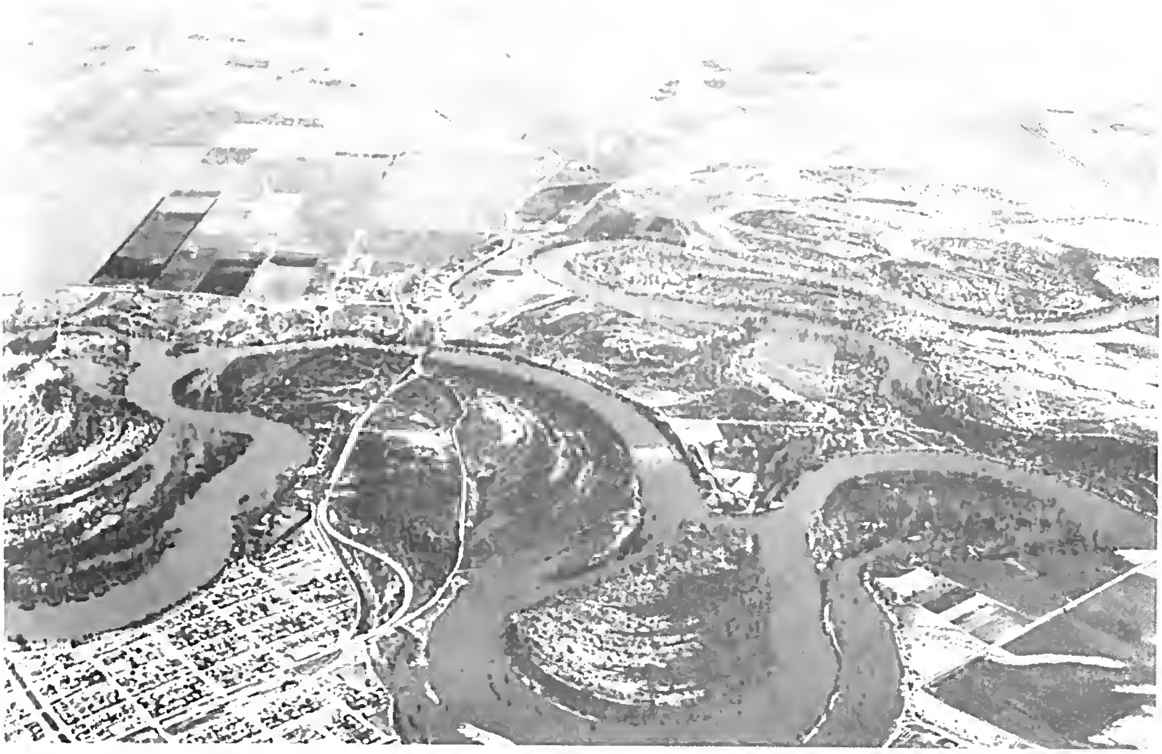
Above — Murray River, Waikerie, within gorge tract; showing cliff-forming Morgan Limestone, and at the top slope-forming Blanchetown Clay capped by Bakara Calcrete. Saline seepages occur on the Blanchetown Clay. (Photo: E. P. O'Driscoll.)

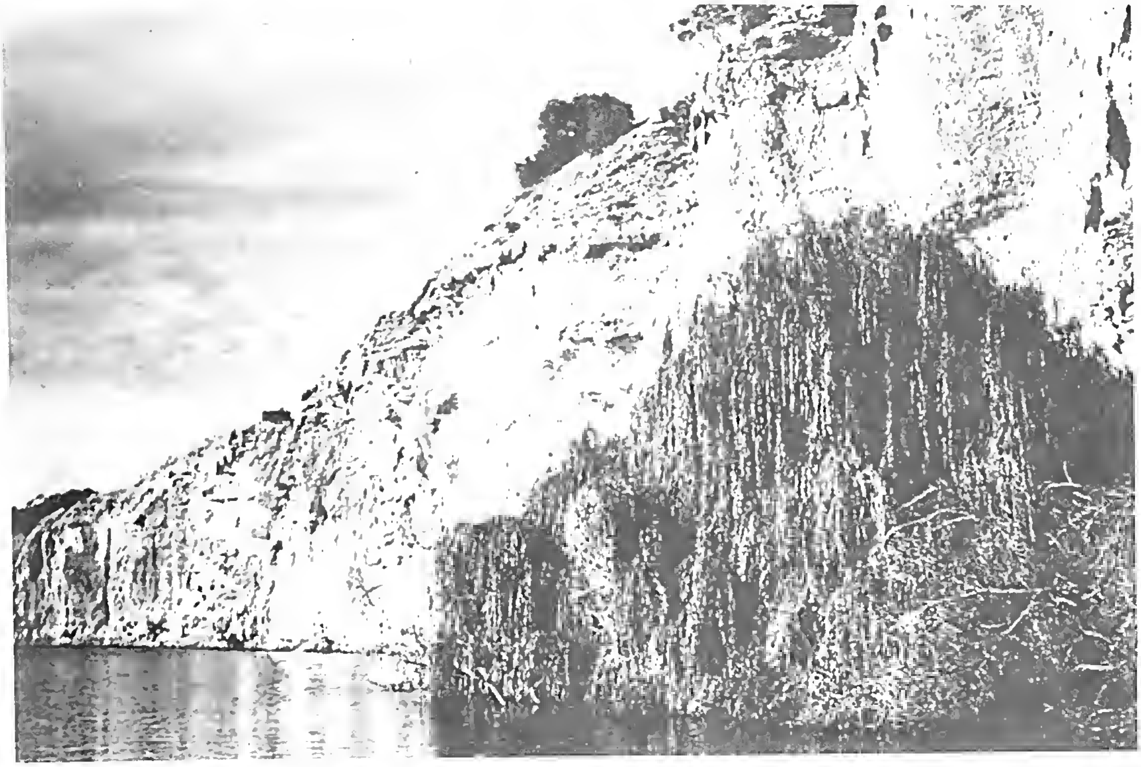
Below — Murray River, Swan Reach; gorge tract with cliff of Mannum Formation and Morgan Limestone; Norwest Bend Formation and Bakara Calcrete at top. (Photo: C. R. Twidale.)

Plate 8

Above — Murray River, Walker Flat; gorge tract with cliff mainly of Mannum Formation; oyster beds of Norwest Bend Formation at top. (Photo: C. R. Twidale.)

Below — Murray River, 6.4 km northeast of Mannum; gorge-side and outer ridges of Mannum Formation, with 'cliff-side channels' between; lagoon and river channel beyond, looking northeast: note absence of cliffs in gorge-tract here. (Photo: J. M. Lindsay.)





Gill (1973a, b), but detailed correlation with the glacial chronology is still unproven and tentative.

Earth movements were at times significant in addition to glacio-eustasy. In the early Pleistocene, for example, the Pinnaroo Block (Figs. 1, 4) was established as a positive topographic feature bounded on the southwest by the Marmon Jabuk and Kanawinka (?fault) scarps and bordered on the west, north and east by riverine and lacustrine plains. On these lowlands, through which the ancestral Murray flowed, Blanchetown Clay and then the thin Bungunnia Limestone were deposited, the latter at least in 'Lake Bungunnia' (Firman 1965, 1971a, 1973) which largely drowned the early Pleistocene river (Fig. 4).

An Early to Middle Pleistocene Murray: Glacio-eustatic low sea levels caused the Murray to incise its bed, and erosion seems to have predominated, but fragments of the earlier Murray valley are preserved in places. Thus Firman (1973, p. 39) noted that 'below the Ripon Calcrete are remnants of an old drainage pattern which extends from Murray Bridge north as far as Morgan'. These 'fossil streams now stranded high in the Murray Cliffs' were seen by him to represent a 'drainage pattern . . . probably developing until such time as Pleistocene faulting along the Marmon Jabuk scarp severed the main stream course near Murray Bridge'. Firman maintained that subsequent blanketing by loess, and the formation of Ripon Calcrete, destroyed the continuity of this river system; but this is debatable.

Dating of the Ripon Calcrete, and hence of this drainage pattern beneath it, has been assisted by preliminary palaeomagnetic results from the Naracoorte-Robe area (Cook *et al.* 1977). These results, taken in stratigraphic context, suggest an age for the Ripon near to the Brunhes-Matuyama palaeomagnetic reversal (700,000 years). A notable glaciation ('one of the longest glaciations of the Pleistocene') is recorded by climatic stages 16-18 of Shackleton & Opdyke (1973), dated by them as 592,000-688,000 years B.P. Granted the association between glacio-eustatic low sea level, loess distribution, and calcrete formation (e.g. Firman 1967, p. 173), this is a reasonable possibility for the time of formation of Ripon Calcrete.

Extension and Incision of the Murray: During these lowerings of sea level by some 100-150 m compared with the present (Shackleton & Opdyke 1973, Chappell 1976), most of the continental shelf west of the Padthaway Ridge was repeatedly exposed. The Murray River extended its course across the shelf (cf. Sprigg 1947, Plan 4, Firman 1969, Fig. 104) and by generating turbidity currents, initiated the formation of the Murray submarine canyons (Fig. 1) down the relatively steep continental slope which drops 4,500 m in 60 km (Sprigg 1947, 1963, Conolly & Von der Borch 1967, Von der Borch 1968).

The lowered sea level also caused incision of the river, together with the development and headward recession of the gorge. The gorge-like character of the new valley was caused first by the calcareous nature and massive bedding and jointing of the Miocene strata in which the feature is mainly eroded, for these properties allow the development of steep cliffs and also inhibit the evolution of tributaries likely to eliminate the steep valley sidewalls. The aridity of the area also assists in this regard, and the undercutting achieved by the river itself, winding about on its own flood plain, is also partly responsible for the steep sidewalls of the valley. But it was the glacio-eustatic lowerings of sea level, the base level of erosion for all exoreic streams, that made possible the essential incision.

Though the Murray and its major tributaries incised their beds, and the regional water table fell, the predominantly calcareous nature of the Miocene strata that underlie most of the western Murray Basin caused the Murray Surface, graded to the Norwest Bend Formation estuary, to remain essentially intact. No doubt the aridity that prevailed through much of the Quaternary also helped in this regard.

The cutting of the gorge left the Murray Plains virtually untouched, but the lowering of the regional water-table allowed deep through-drainage and the development of a few comparatively small caves and numerous solution and collapse dolines. In general, however, because of the aridity and the impurity of the Miocene limestones, karst forms are poorly represented.

The river apparently did not erode the gorge in one phase but instead, in early to middle Pleistocene times, cut a comparatively shallow gorge which extended only as far upstream as Chucka Bend or thereabouts. This is indicated by the distribution of sediments laid down in the early to middle Pleistocene Lake Bungunnia (Fig. 4). Thus at this time the ancestral Murray still flowed in the original shallow valley as far south as Purnong. That shallow valley was drowned by Lake Bungunnia, which most likely developed by the damming effect of regional uplift along the Marmon Jabuk Fault (Figs. 1, 4; see also Mills 1964, Twidale & Bourne 1975). Further middle Pleistocene earth movements, on the Morgan Fault at the edge of the Cambrai Block, displaced Ripon

Calcrete during the formation of younger calcretes in the palaeosol, the Bakara Pedoderm (Firman 1973, pp. 32, 33).

Linear depressions interpreted differently by various authors, but here seen as erosional 'cliff-side channels' (Steel 1962, Frahn 1971, Thomson 1975) also formed during the incision of the gorge (Pl. 8 below, Fig. 6). Steel interpreted those at Teal Flat as slump structures. Thomson concluded that they are meander caves (Jennings 1970) modified by collapse and slumping. However, their general morphology and limited distribution between Scrubby Flat and Pompoota suggest that they were formed when the river was braided, rather than meandering. Moreover since braiding supersedes meandering when either gradient or discharge is increased, the channels, although of uncertain age, are best explained as due to localised steepening of the river bed (Leopold & Wolman 1957, Twidale 1966) consequent on renewed uplift of the Marmon Jabuk structure.

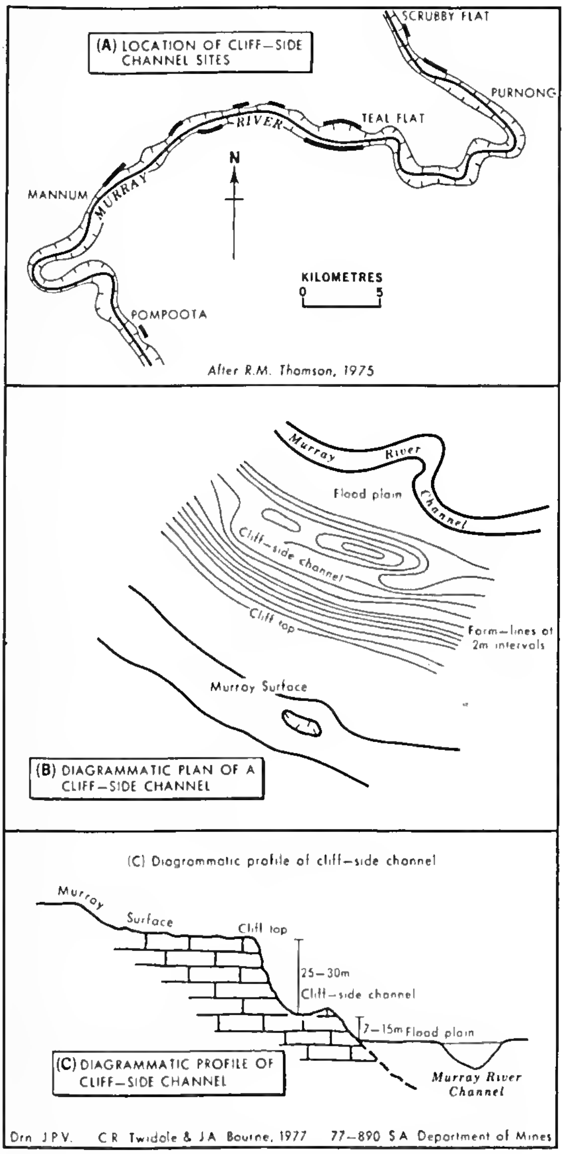


FIG. 6 — Location, diagrammatic plan and profile of 'cliff-side channels'.

The deepened gorge, which was ultimately incised as much as 65 m below the present valley floor (Fig. 2), extended headwards through the late Pleistocene, eventually breaching the limestones at Overland Corner which had been uplifted along the Murrayville Monocline.

Exhumation of Older Forms: During its Quaternary incision the river exhumed several small relics of ancient granitic landforms which had been buried by the advancing Oligo-Miocene seas and the sediments deposited therein. The river bottoms on granite at Murray Bridge (Sprigg 1952, Johns 1960, 1961) (Fig. 2C), and some 5 km upstream from Mannum an old domed inselberg, its surface pitted and grooved, is revealed from beneath the limestone cover. Granite boulders and other outcrops occur at several sites near Murray Bridge where the foundations of the new bypass bridge at Swanport are excavated partly in granite. Some of the right-bank tributaries, notably Reedy Creek, have similarly resurrected forms developed in Lower Palaeozoic crystalline rocks (Saies 1968).

Late Pleistocene and Post-Glacial Events: During the last glacial maximum (22,000-14,000 years B.P.) relatively arid conditions replaced the moist pre-glacial climate in southeastern Australia (Bowler 1976), but no doubt, then as now, the flow and erosive power of the Murray depended on precipitation and snow-melt on the Eastern Highland source-areas, irrespective of the aridity of the country traversed downstream. Growth of linear sand dunes was activated during this arid period (Bowler 1976), and the late Pleistocene east-west dunefields of Woorinen Formation in the Murray Basin (Lawrence 1966, Firman 1973) are assigned to this time. Horizons of silty and earthy carbonate in Woorinen Formation (and Pooraka Formation) comprise the Loveday Pedoderm (Firman 1973, Gill 1973b) and represent soil formation from widespread deposits of loess. Earthy carbonates from late phases of the Loveday Pedoderm in Woorinen Formation have yielded ^{14}C dates of 14,200 + 790 B.P., and 16,400 ± 450/560 B.P. (Gill 1973a). At the proposed Chowilla damsite (Fig. 2A), 'deposits of stranded high-level meanders' recognised by Firman (1973),

relate to a precursor of the Murray River and are overlain by Woorinen Formation with Loveday Pedoderm.

The post-glacial rise of sea level (Flandrian Transgression) between 17,000 and 6,000 B.P. caused the Murray River to aggrade its valley to the rising base-level by depositing coarse-grained quartz sands of the Monoman Formation ('lower valley fill') (Firman 1966, 1973). The subsurface type sections of the formation are derived from foundation test holes drilled along the axis of the proposed Chowilla damsite, but the unit has also been penetrated in bridge-site drilling at Swan Reach and Murray Bridge (Fig. 2B, C). A femur of *Phascolonus* cf. *P. gigas* Owen, the giant wombat, and a vertebral centrum close to *Macropus ferragus* Owen, both extinct forms, have been identified from low in type Monoman Formation and tentatively dated late Pleistocene (Marshall 1973). Gill (1973a) recorded a ^{14}C age of 7,200 ± 140 B.P. for a log of *Eucalyptus largiflorens* (Black Box) from higher in Monoman Formation at the same locality, and dated the unit uppermost Pleistocene/lower Holocene as shown in our Table 1.

Younger valley fill of Coonambidgal Formation (Lawrence 1966, Firman 1971a, 1973) comprises fluvial clays, silts, and sands, generally finer-grained than Monoman Formation. Sub-fossil wood from basal Coonambidgal Formation at the Chowilla damsite yielded a ^{14}C date of 4,080 ± 100 B.P. (Firman 1967). Gill (1973a) recorded a 'disconformity between Coonambidgal Formation and Monoman Formation at Chowilla Damsite marked by fossil trees and oxidation of underlying sediments', correlated with a mid-Holocene phase of terrain instability and climatic oscillation. At Swan Reach, Firman (1971a, 1973, p. 42) described aeolian Bunyip Sand overlying shell-bearing Tartangan Beds ^{14}C-dated 6,020 + 150 B.P. by Tindale (1957), and underlying Coonambidgal Formation. It is likely that at least the initial accumulation of Bunyip Sand dunes and veneers took place during the same mid-Holocene phase.

The present flood plain is of course inundated at times of high water. In 1956 for instance the river flooded into the main street of Mannum and reached to the ceilings of ground floor rooms. The river then stood some 7 m above its normal level (Fig. 2B), but in prehistoric times, a flood dating from about 3,000 years ago clearly attained a higher level than that of 1956 (Mulvaney, Lawton & Twidale 1964).

The completion of the Murray Barrages in 1944, intended to control the ingress of sea water into the Murray system, caused a rise of about 0.6 m in the river level as far upstream as Blanchetown. Many river redgums have been drowned in consequence and many meadows and prime grazing lands have been converted to lagoons and swamps.

CONCLUSION

The development of the Murray River can be traced back some 3 m.y. to the middle Pliocene. The course of the river both in gross and in detail is determined largely by structure, but the essential gorge-like character of most of the valley in South Australia is the result of glacio-eustatic lowerings of sea level during the Pleistocene. The truncation of the river, the drowning of the lower part of the valley and the infilling of the lower part of the valley floor, all reflect the post-glacial rise in sea level.

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4

EVOLUTION OF THE MURRAY RIVER DURING THE TERTIARY PERIOD. EVIDENCE FROM NORTHERN VICTORIA

By P. G. MACUMBER*

ABSTRACT: Contours of the pre-Tertiary surface under the southern Riverine Plain in Victoria show elongated depressions (valleys?) suggesting that a drainage system ancestral to the present Murray system was in existence in Eocene times. The position of the bedrock depressions indicates that in Victoria the basic physiographic divisions and fluviatile provinces were established in the early Tertiary and have changed very little since that time.

From Oligocene to early Miocene time it is not possible to demonstrate the presence of a co-ordinated drainage system because the Murray Valley was then probably little more than a swamp. In late Miocene times a co-ordinated system (deep leads) re-appeared and this system flowed into a deep marine embayment in the vicinity of Cohuna in northern Victoria. Aggradation of the deep leads is attributed to rising base levels associated with the onset of the late Tertiary marine transgression.

INTRODUCTION

Before any meaningful discussion on the Tertiary evolution of the Murray River system it is necessary to consider physiographically, what is the Murray River. For instance we might ask which system during the Eocene would be the Murray River if an upper Murray system consisting of the Murray-Indi, Mitta Mitta and Kiewa Rivers passed northwards to become tributary to the Moulamein-Billabong system while the lower Murray consisting of the Ovens, Goulburn, Campaspe, and Loddon Rivers remain linked as they are today.

Furthermore on a more detailed level it is clear that even in the late Quaternary there have been significant alterations in the course of the Murray River (Pels 1966). Our ability to determine which of the multiple river courses on the surface of the modern plain is the true Murray River depends almost entirely on the capacity to trace, visually, an individual course. Even so, given the tendency for the re-occupation of earlier meander belts by succeeding (and often different) rivers, this is difficult. It becomes virtually impossible when attempting to reconstruct the deeply buried Tertiary river systems.

With this highly dynamic and transient setting it would be pointless to choose a given combination of river systems at each point in time and to call it the Murray River.

A broader approach must therefore be adopted in which regional physiography, stratigraphy and sedimentation provide a generalized picture of the overall Tertiary drainage system. Thus for the purposes of this paper the broader physiographic province — the Murray Valley (or Plains) is considered a more attainable objective, and the Murray River is defined as the co-ordinated river system occupying the Murray Valley.

GEOLOGICAL SETTING

Continental sedimentation began in northwest Victoria in Palaeocene times and had extended throughout the Murray Basin by the Eocene (Lawrence & Abele 1976). It has persisted in the eastern parts of the basin up to the present day. In the west, however, paralic sedimentation commenced in late Eocene times and continued until late Oligocene, when the earliest marine sediments are recorded. Marine sedimentation continued until the middle Miocene when the sea retreated from the basin, prior to transgressing again in late Miocene to early Pliocene times before finally retreating (Abele *et al.* 1976).

The two-fold sedimentologic division of the Murray Basin that came into being in late

* Geological Survey, Victorian Department of Minerals & Energy, 109 Russell Street, Melbourne, Victoria, 3000.

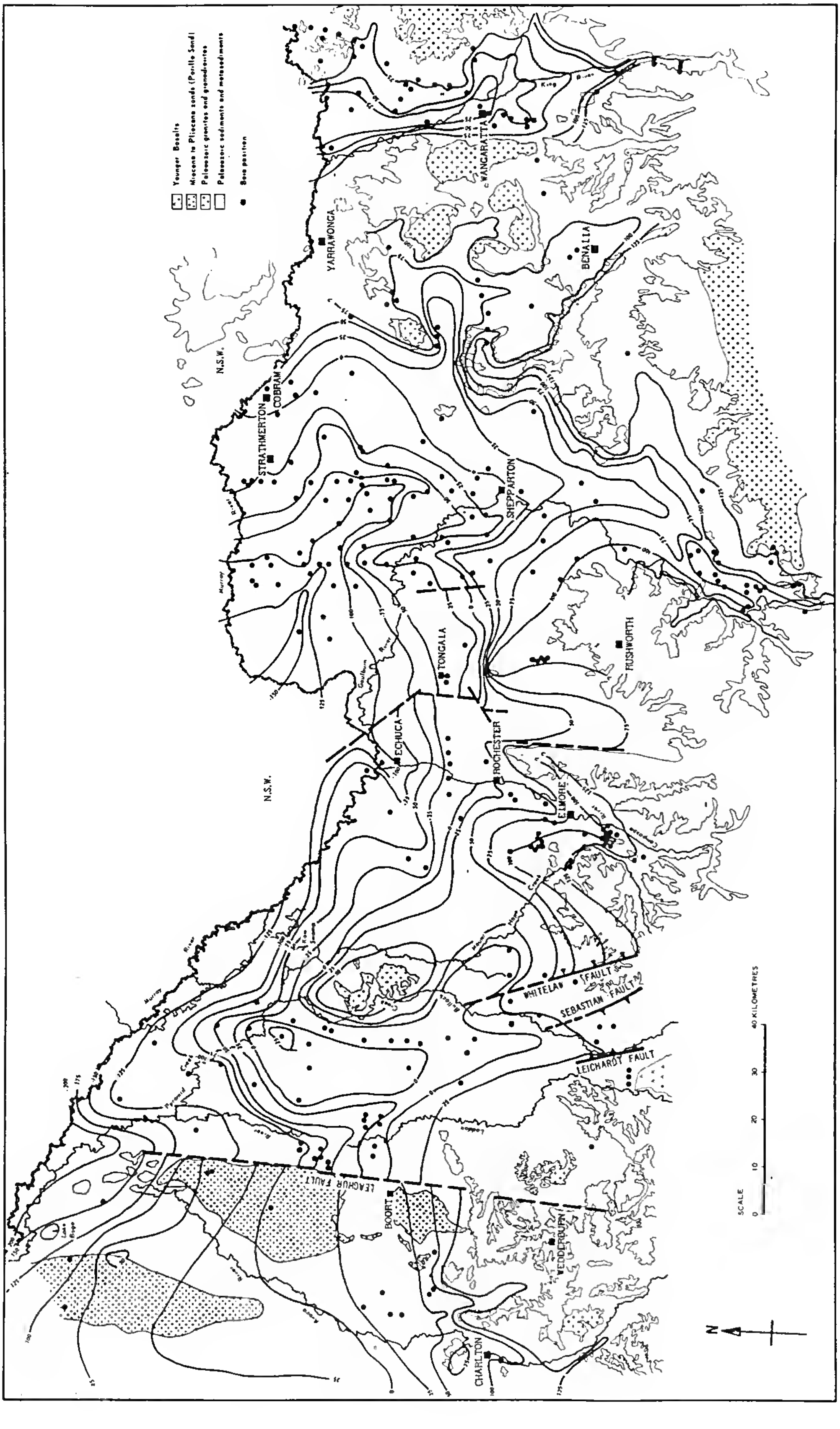

FIG. 1 — Structure contour map of Palaeozoic basement under the southern Riverine Plains in Northern Victoria. (Eastern parts from Tickell 1978.)

Oligocene times persists today, with fluvio-lacustrine sediments being deposited in the eastern (Riverine) parts whilst aeolian sedimentation predominates in the Western (Mallee) area previously covered by the marine transgression.

It is clear that the present day Murray River, upstream of its junction with the Murrumbidgee is essentially a westerly flowing connector linking the northerly and north-westerly flowing (Victorian) tributary systems — passing from the Indi River westwards to the Loddon River.

EARLY TERTIARY SYSTEMS

Upstream of its junction with the Murrumbidgee the present day Murray River is fed by Victorian streams. It is an east to west flowing trunk system linking the various north flowing tributaries rising in the Victorian highlands. The history of the Murray River is thus directly related to its principal tributaries. During the Eocene the earliest identification of a Murray River is as a fully developed tributary system which passes plainwards from embayments in the highlands, to become at least a partly co-ordinated trunk system further out on the plains.

Structure contours of the pre-Tertiary surface under the southern Riverine Plain in Victoria reveal depressions (valleys) suggesting that a similar drainage pattern directly related to the present system was in existence in early Tertiary times. Early Tertiary valleys can be traced down-basin from the point where the modern river valleys emerge from the highland front, to a position beyond the present day Murray River (Fig. 1).

The position of the valleys indicates that in Victoria the basic physiographic divisions and fluviatile provinces were established by Eocene times and have undergone relatively little modification since then. This is consistent with the view of Hills (1934, 1975) who considered that the uplift of the Eastern Highlands had largely occurred by early Tertiary times, and also the work of Wellman (1974) who stated, 'As a result of K-Ar dating of the valley filling (basalt) flows (in eastern Victoria) it has been shown that by the Oligocene the highlands were already in existence and possessed a relief of 1000 m with a drainage system similar to that of present day'. It seems likely that the basal valleys of the Riverine Plain are the downstream extensions of the early Tertiary highland valleys recorded by Wellman and Hills.

It is not known to what extent the basement valleys are erosional and to what extent structural. However it is probable that both factors have been variously operative. For instance Tickell (1978) notes that the present day distribution of Permian rocks southwards into the Campaspe, Goulburn and Ovens-King valleys suggests that the positions of the valleys were determined to a large degree by the same structures which preserved the Permian rocks. Similarly in the Loddon Valley the confinement of Permian glacial sediments to a narrow band within the highland tract of the Tertiary Loddon River has led the author to conclude (Macumber 1978a) that faulting has played a significant role in the development of the Loddon Valley in late Tertiary times.

The significance of structural control in the continued development and deepening of the basement depressions is well illustrated in the case of the lower Loddon Valley where there is a concordance of levels between the uppermost surface of the Tertiary Renmark Group sediments, deposited within a slowly subsidising graben, and the adjacent stable Palaeozoic surface. This had led to the development of an extensive plain, the Mologa Surface (Macumber 1978b), formed across both Tertiary sediments and peneplaned Palaeozoic sediments. The Mologa Surface has been identified below all of the central Loddon Plains and part of the Campaspe Plains.

The bedrock valleys are overlain (infilled ?) with carbonaceous sediments, the Renmark Group, which range in age from Eocene at the base to middle Miocene at the top (Lawrence 1975, Martin 1977). Sedimentation began with the deposition of a predominantly quartz sand lithofacies (Warina Sand, Lawrence 1975), although gravel, ligneous clays and silts, and minor lignites are present (Figs. 2 & 3). Lawrence noted that when the Warina Sand was deposited the primary control appears to have been the drainage pattern. In some instances the Renmark Group sediments can be traced up into the highland tracts of the valleys. Tickell (1978) notes 'Ligneous clays and gravels which are encountered in the Campaspe and Goulburn valleys . . . can be traced down the valleys and are thought to be continuous with (the Renmark Group)'. The picture is not so clear in the Loddon Valley, because immediately upstream of the highland front, the valley is backfilled with the coarse grained quartz gravels and pebbles, the fluviatile 'deep lead' facies of the upper Miocene Calivil Formation (Macumber 1973). If any of the Renmark Group sediments existed they must have been removed from the highland tract by late Tertiary stream activity. It is notable that coarse quartz gravels and pebbles so typical of the Calivil Formation are not a prominent component of the

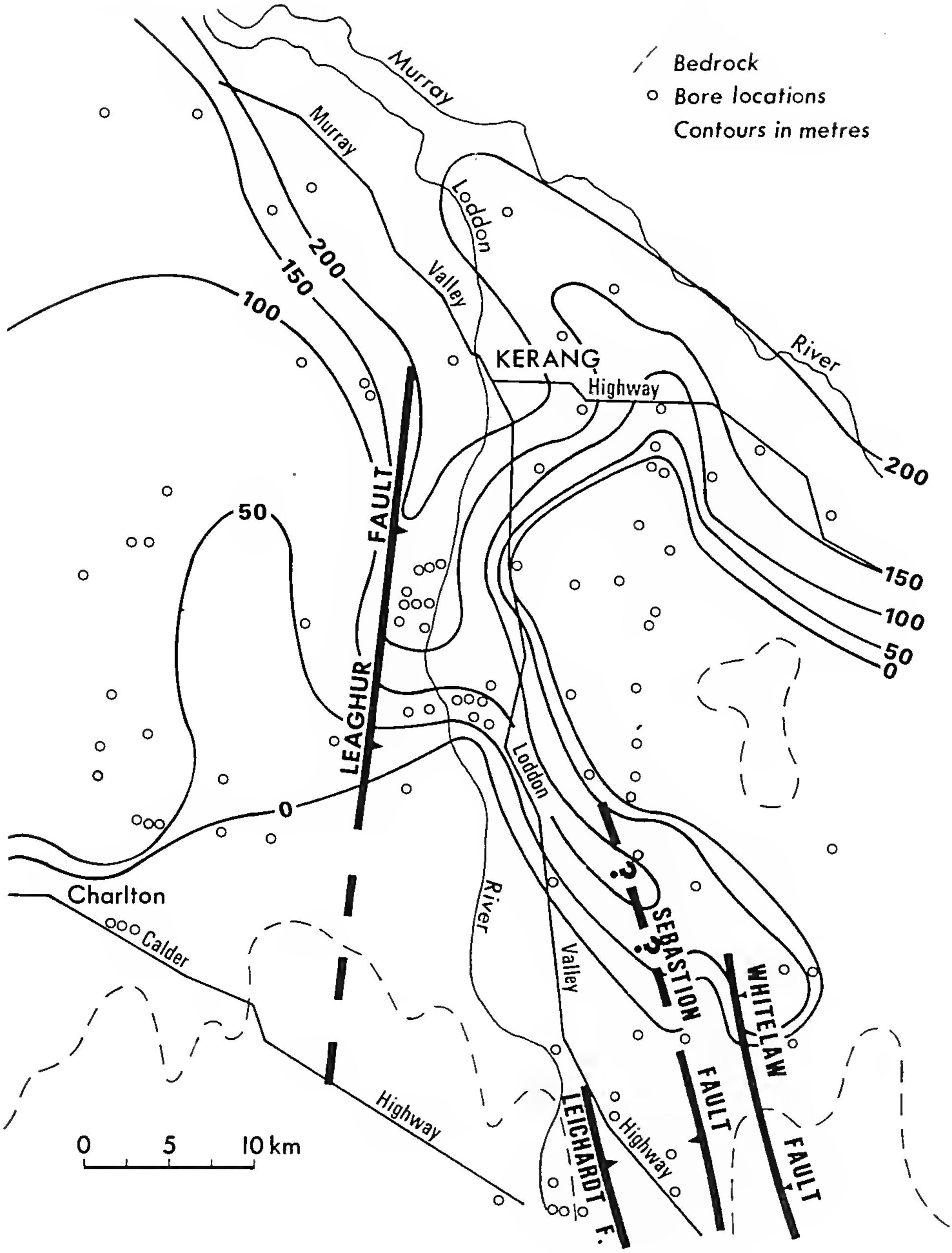

FIG. 2 — Isopach map of the Renmark beds in the Loddon Valley.

sediment infilling the older Tertiary depressions and are usually absent from the sequence.

The investigation of the nature of the down-basin continuation of the early Tertiary systems was restricted by the presence of the State border. However the well-defined character of the tributaries suggests that at least a partly co-ordinated drainage system and therefore a Murray River existed in the eastern Murray Basin in early Tertiary times.

Wherever the Warina Sand is found in the Murray Basin, it is overlain by the Olney Formation (Lawrence 1975) which consists of carbonaceous clay, silt, lignite and sand. Lawrence concludes that the Olney sediments were deposited in deltaic, lagoonal and tidal flat environments. However in the absence of either marine or paralic conditions in the eastern part of the basin, it is concluded that lacustrine and paludal conditions were dominant.

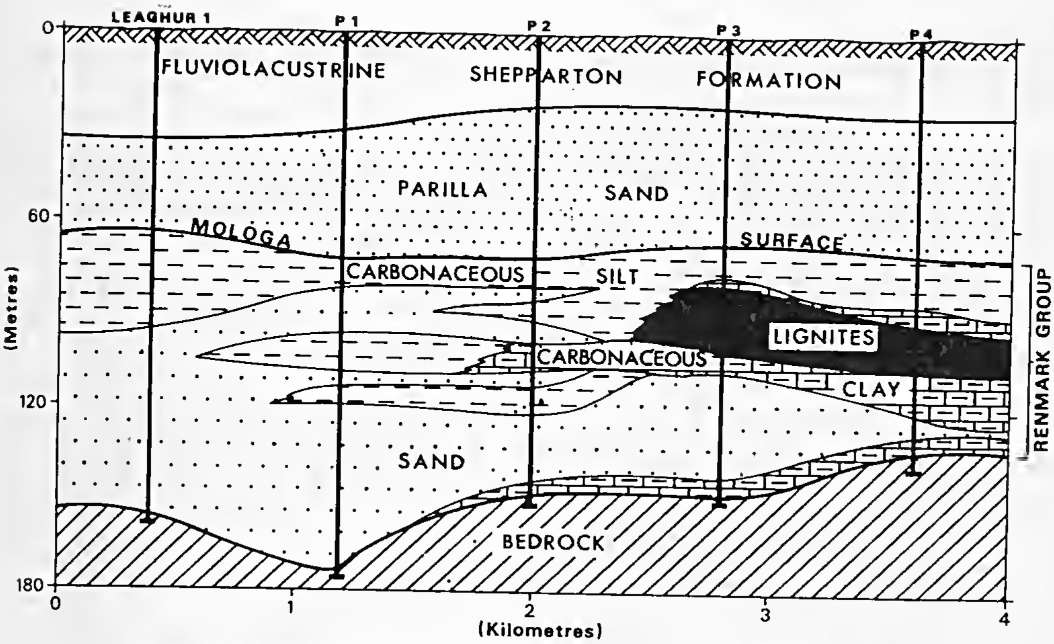

FIG. 3 — Cross section through the western Loddon Plains at Leaghur.

Martin (1977) has placed the upper limits of carbonaceous sedimentation in the eastern part of the Murray Basin as middle Miocene. Martin comments on the latter phases of Renmark Group sedimentation 'This ancient lacustrine landscape is middle Miocene in age and the overlying fluviatile sediments include late Miocene, Pliocene and Pleistocene deposition'. The presence of lagoonal environments close to the highland front indicates a major shift in stream regime whereby the earliest co-ordinated drainage of the Eocene system was replaced by uncoordinated drainage in the Oligocene. These conditions were maintained until middle Miocene times, indicating that during this interval the Murray Valley was essentially an extensive swamp.

LATE TERTIARY SYSTEM: THE CALIVIL FORMATION

The late Miocene to early Pliocene drainage system known to the early gold miners as the 'deep leads' is undoubtedly the best documented of the Tertiary river systems (see Hunter 1907). Elements of this system have been traced northwards under the present day Riverine Plain to where they once flowed into a late Tertiary sea which had advanced up the Murray River to Cohuna in the far north of Victoria (Macumber, in press).

A distinctive suite of coarse grained quartz sands and gravels termed the Calivil Formation (Macumber 1973), which was deposited by this system, forms the major aquifer for downbasin groundwater movement from recharge zones in the Victorian Central Highlands.

Physiographically the various tributary drainage basins which first appeared in the early Tertiary were well established by late Tertiary times and since then these systems have not been further modified to any extent.

Within the highlands the Calivil Formation sediments are confined to the major valleys incised into Palaeozoic basement. However on passing across the plain the Calivil sands and gravel form sheet deposits because the river systems were less confined and hence fanned out (Fig. 4). In the northern areas adjacent to the present day Murray River it is not obvious at which point the individual tributary fluviatile provinces merge into a trunk Murray province. Because of the migratory character of the systems this point could be expected to be fragmented, and therefore an arbitary line is taken which corresponds to the zone where individual south-north sand tongues merge to make a continuous east-west sand sheet.

Below the Loddon Plains, unconfined fluvial deposits of the Calivil Formation are found only in the south and central parts of the plain, but in the northern areas deposition is restricted to a deep bedrock trench which is an extension of the highland valley. The trench was formed in late Miocene times when a rejuvenated Loddon River cut its course across the middle Miocene Mologa Surface which at that time constituted the Loddon Plain (Macumber 1978b). The trench cuts across

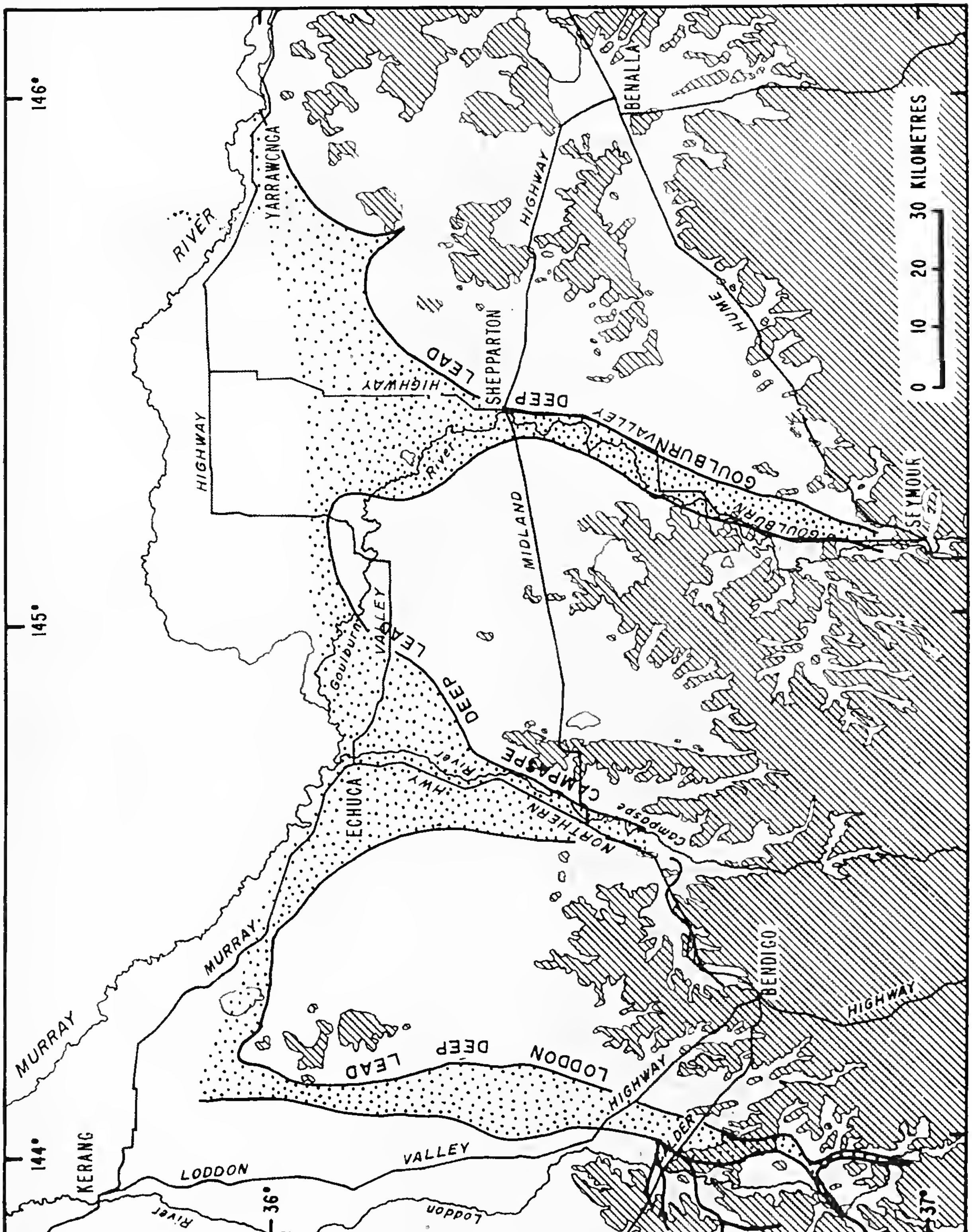

FIG. 4 — Position of the 'Deep Leads' under the Riverine Plain.

both Palaeozoic sediments and Renmark Group sediments (the Olney Formation) before meeting a northwest trending Murray Valley near Cohuna (Fig. 5).

It is notable that the thalweg of the base of the late Tertiary Loddon Valley 'deep lead', from its source on the Divide to its point of junction with the Murray Valley system, has essentially the same gradient as the present day Loddon River. Given the differing physiographic tracts from the Divide to the sea there is a fairly uniform depth of valley fill throughout ranging from about 90 to 120 m in thickness.

This supports Wellman's contention (1974) that the present (late Cainozoic) uplift of the Victorian Highlands may extend only from the southern margin of the highlands to about 40 km north of the Main Divide. It goes one step further however, in suggesting that there has been no significant uplift of the Victorian Western Highlands since at least late Miocene times.

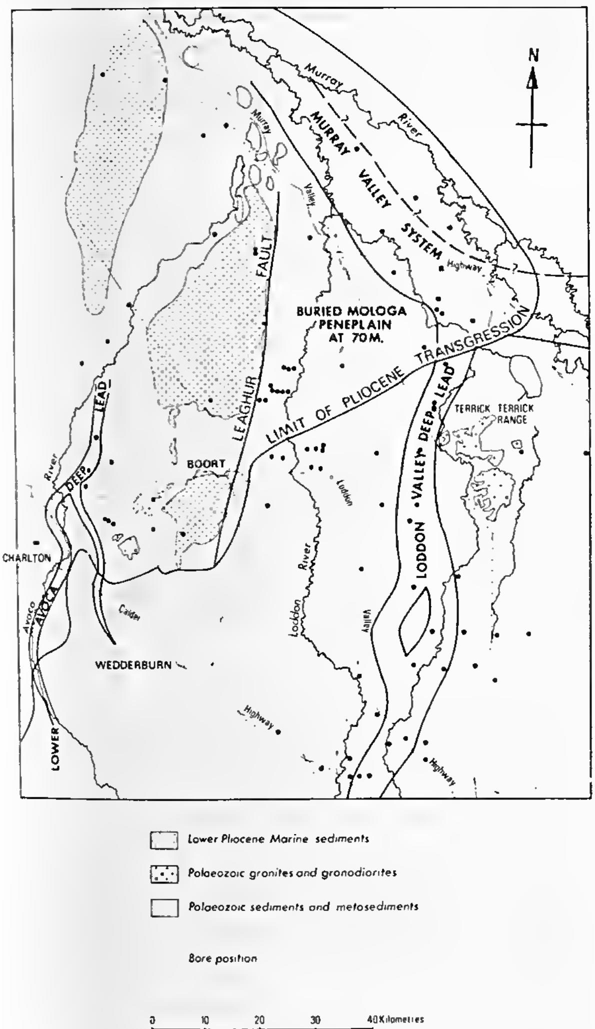

FIG. 5 — Late Tertiary palaeogeography of the Avoca and Loddon Plains in Northern Victoria.

At its downstream limits the coarse sands and gravels deposited within the trench of the confined Loddon system merge with similar sediments of the ancestral Murray system. In the Gunbower West No. 2 bore drilled 8 km south of Cohuna, sands and gravels occurring from 87 to 107 m are taken to represent deposits of the late Tertiary Murray River system. As is the case in the central Loddon Valley, the gravels overlie fine grained carbonaceous Renmark Group sediments.

The change in fluvial province from the Loddon Valley to the Murray Valley is reflected in an abrupt change in water salinities of the Calivil Formation. In the Loddon Valley salinities gradually increase downbasin, to over 10,000 mg/litre t.d.s. However beyond the junction with the better quality Murray Valley aquifer, salinities of the Calivil Formation fall to 4,000-6,000 mg/litre.

The gravels and sands in the Cohuna-Kerang district are downbasin equivalents to similar sediments found to the southeast in the parishes of Wharparilla and Echuca North.

Downstream, beyond Cohuna, coarse grained channel sediments of the Murray Valley system can be traced in a northwest direction towards Swan Hill. The distribution of bores does not permit the detailed understanding of depositional constraints as is the case for the Loddon Valley but a sharply defined southern limit of the Murray Valley is indicated.

Downstream beyond Cohuna, the Calivil Formation is directly overlain by late Miocene to early Pliocene marine sediments — the Parilla Sand. This unit was originally defined by Firman (1965) in South Australia as a fluviolacustrine deposit, and in Victoria it has been broadened by Lawrence (1976) to include the Victorian equivalents of the marine Loxton Sand of South Australia (Ludbrook 1957). The Parilla Sand was deposited during the short-lived late Miocene to early Pliocene transgression which swept across northwest Victoria.

At its most easterly area of outcrop, on the Gredgwin Ridge west of Kerang, the Parilla Sand consists of cross-bedded fine to coarse grained micaceous quartz sands overlying fossiliferous silts. Heavy mineral bands up to one metre thick are interbedded with the sands.

The upper part of the Parilla Sand has been deeply weathered and poor preservation of the fossils limits their diagnostic and chronologic

usefulness. In general the bulk of the material consists of mullusca (predominantly pelecypods) including *Dosinia (sensu lato), Gari?* and tellinids. All the valves are disarticulated and crowded convex down along the bedding plains, suggesting a beach or near beach depositional environment. Plant material is also present including complete leaves. The only fossil of diagnostic value so far obtained is the echinoid *Lovenia woodsi* which was found by the author at a quarry 11 km west of Kerang. Elsewhere in Victoria, *Lovenia woodsi* is considered to indicate a late Miocene to early Pliocene age.

Although the Gredgwin Ridge is the Parilla Sand's most easterly outcrop in the Murray Basin, it has been traced eastwards beyond Cohuna under the Quaternary sediments of the Loddon Plains (Macumber 1969). There is no marine sediment in the Wakool bores 36078 and 36102, situated in New South Wales to the north of Cohuna, and the nearest marine sequences recorded in N.S.W. bores are at Balranald about 80 km to the west (Martin 1977). It seems that the sea transgressed up the late Miocene Murray Valley, and at its height, a deep marine embayment covered the lower Loddon Plains, with its most easterly limits passing just inland of the junction of the Loddon and Murray river systems (Fig. 5).

At this stage the Murray Valley downstream from Cohuna was drowned; the lower Loddon and Murray river systems upstream from this point were estuarine. West of Cohuna the Calivil Formation gravels deposited by the Murray River system are directly overlain by, and partly intertongue with, the Kerang Sand Member of the Parilla Sand. In the Kerang area, the Kerang Sand is the basal, transgressive unit in the marine sequence and consists of fine to coarse grained micaceous sands formed in part by re-working of the Calivil Formation. The Kerang Sand is overlain by a clay and silt unit (Tragowel Member) and this in turn is overlain by a predominantly fine grained micaceous sandstone (Wandella Sandstone). This three-fold subdivision of the Parilla Sand is taken to represent

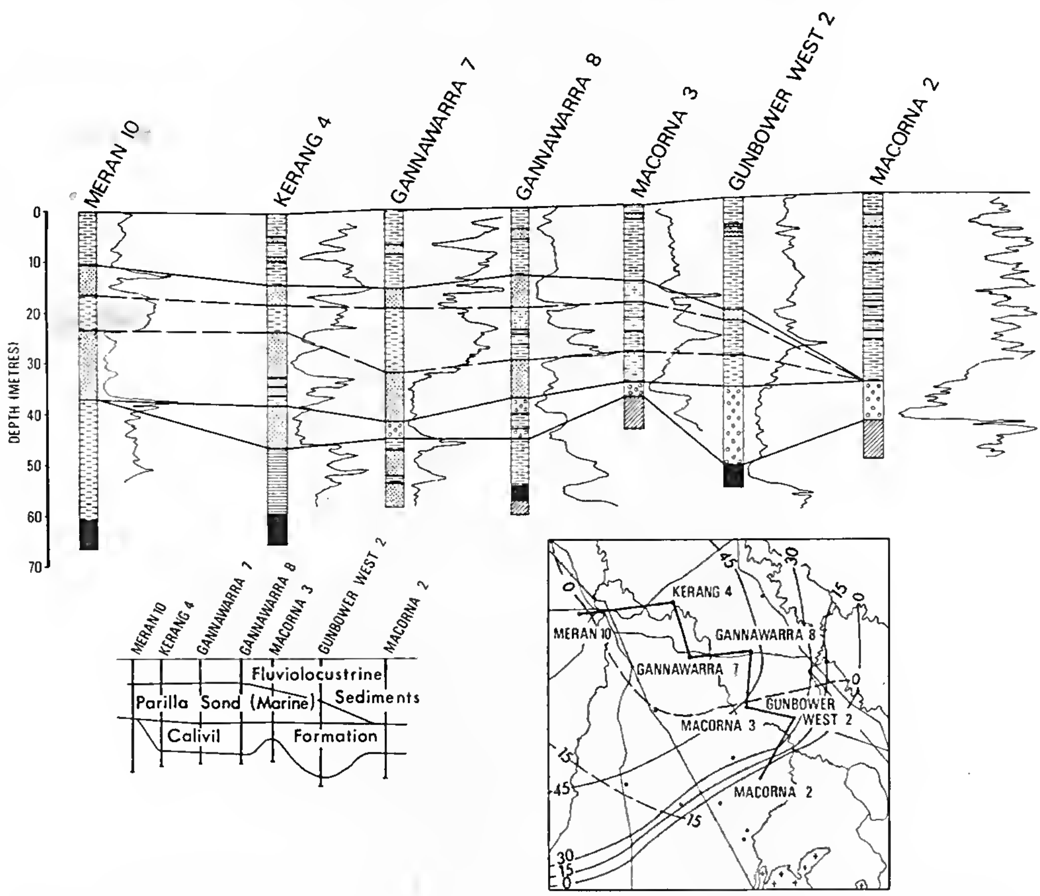

FIG. 6. — Stratigraphic section through the lower Loddon Plains. Lower right, locality plan and isopach map of Parilla Sand.

the form of the transgression-regression cycle at the extreme limits of the transgression up the Murray Valley (Fig. 6).

While the Parilla Sand outcropping on the Gredgwin Ridge is clearly marine, eastwards towards the limits of the transgression deltaic and estuarine elements associated with Murray and Loddon river systems would also be present. No attempt is made to differentiate these various environments. The situation on the Murray Valley system is similar to that described by Taylor (1895) as occurring at Stawell in Western Victoria where marine fossils were found overlying the deep lead sediments at the Welcome Rush, Poverty Hill and Four Post. Taylor commented, 'Before its subsidence below the sea, the original schist country, on which the marine beds were subsequently deposited, was naturally an undulating surface, with its own system of valleys and their tributary branches. They were then filled by the marine drifts, covering the older pre-existing drifts'. He also states, 'The Welcome Rush I believe to have been a fluviatile deposit, since covered by a marine deposit'.

The gradually rising base levels that accompanied the transgression led to fluvial aggradation within the Murray and Loddon Valleys. The nature of the aggradation is best illustrated in the Loddon Valley where the late Miocene Loddon River was confined to a deep trench incised thirty metres into the pre-existing middle Miocene Mologa peneplain. The trench was completely backfilled during the transgression and then buried under coastal plain deposits. In general the trench sediments consist of a thick suite of fluvial gravels and sands. In the far north however, closest to the shoreline, the valley is not entirely backfilled with coarse grained deposits but instead the final material is a dense clay valley plug. On passing up-valley the gravel sequence rapidly thickens, and at the highland front is three times its thickness far out on the plain. An explanation for the down-valley wedging of the gravels is seen in the gradual rise in base level of aggradation causing the deposition of finer grained sediments in a gradually retreating flood plain environment developed as a coastal plain. Thus as flood plain environments existed in areas marginal to the advancing sea, coarse valley sedimentation continued uninterrupted up stream beyond the influence of the rising sea level.

Three closely drilled sections across the shoreline show the thick marine sequence as rapidly cutting out to be replaced by flood plain deposits. It seems that the shoreline remained fixed for some considerable time at its eastern limits where a fine balance had been reached between sea level rise and fluvial aggradation.

The sea retreated from the Murray Basin in the Pliocene leaving the Riverine Plain in Victoria as essentially a basin of internal drainage.

CONCLUSION

Two major phases of valley incision and river development are recognized in the Murray Basin during the Tertiary period. The earliest occurred in Eocene times when a fully developed drainage system passed northwards across the Riverine Plain from highland embayments which are the same as those occupied by present day streams. The Loddon, Campaspe, Goulburn and Ovens river systems were present. The basic physiographic divisions and fluvial provinces of northern Victoria were therefore in existence in the Eocene and have undergone little modification since that time.

A second phase of valley incision and major river development began in upper Miocene times with the establishment of the 'deep lead' drainage system. The Goulburn, Campaspe and Loddon Rivers were tributaries of a trunk Murray Valley system which flowed into a marine embayment near Cohuna in northern Victoria.

Following the marine regression in the early Pliocene the eastern part of the Murray Basin became a basin of internal drainage and remained so until Quaternary times.

ACKNOWLEDGMENTS

I wish to thank Dr. D. Spencer-Jones for permission to carry out this project and Mr. W. A. Esplan for his continued support during the investigation. Mr. T. A. Darragh of the National Museum identified the very scrappy fossils from the Parilla Sand. The figures were drafted by the Draughting Branch of the Victorian Department of Minerals and Energy.

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5

A BRIEF CAINOZOIC HISTORY OF THE UPPER DARLING BASIN

By GRAHAM TAYLOR*

ABSTRACT: The Upper Darling Basin Cainozoic stratigraphy is characterized by two major phases. The earlier, commencing in the late Cretaceous, is a phase of weathering and the formation of two silcretes, one in the early Eocene, the other in early Pliocene. During this phase only limited sedimentation occurred, from Eocene to Miocene, in the eastern parts of the Basin.

During the late Miocene thin but widespread fluvial sheet gravels were deposited. These were a precursor to the second phase which was one of widespread fluvial deposition within the Basin. It began in the late Pliocene and is still continuing. Three formations have been recognised within the fluvial sequence.

INTRODUCTION

Considerable effort has been expended in the Upper Darling Basin (Fig. 1) in delineating the pre-Cainozoic geology of the Great Artesian Basin. The Cainozoic geology has however received little attention. Senior *et al.* (1968), B. Senior (1972), D. Senior (1972, 1973), Idnurm and Senior (1978), Taylor (1976, 1978) have delineated the stratigraphy of the Cainozoic in the Queensland portion of the Basin but the greater part, which lies in New South Wales, has received only passing attention from geologists.

The stratigraphy presented in this paper is based on a small area (*c.* 400 km^2) studied by the author (Taylor 1976), and on re-examination of records of the New South Wales Water Resources Commission. Previous studies of the Cainozoic are restricted to brief accounts of the weathering stratigraphy in the Lightning Ridge area (Whiting & Relph 1961, Offenberg 1968) and Taylor (1978) records the weathering chronology of outcrops on ridges to the west of Lightning Ridge. The Cainozoic stratigraphy of the basin-fill has not been considered by previous authors. Brunker (1967, 1968) and Offenberg (1968) simply record the Upper Darling basin-fill as 'Cainozoic Undifferentiated'. Martin (1969, 1973) has established a chronology based on pollen in sediments from the eastern portion of the basin between Narrabri and Wee Waa.

GEOLOGICAL SETTING

The Upper Darling Basin is the southern portion of the Darling-Warrego Basin of Brown *et al.* (1968). The Cainozoic deposits of the Basin can be considered to be a continuation under different tectonic and sedimentary control of the Mesozoic sedimentation of the Surat Basin. The Darling-Warrego Basin is bounded on the east and south by Palaeozoic rocks of the New England and Lachlan Fold Belts and in the north and west by Mesozoic sediments of the Great Artesian Basin. The Upper Darling Basin is separated in the west from the remainder of the Darling-Warrego Basin by low ridges of Cretaceous sediment. The sediments of the Upper Darling Basin unconformably overlie the Mesozoic sediments of the Surat Basin.

The stratigraphy of the Upper Darling Basin can be conveniently split into a late Cretaceous-early Tertiary period of weathering and localised sedimentation and a late Tertiary to Recent period of widespread fluvial deposition.

LATE CRETACEOUS-EARLY TERTIARY

At the close of deposition of the labile sediments of the Rolling Downs Group (Table 1, Section 4) in the Lower Cretaceous the regional slopes in the Basin were in a generally northeasterly direction (Offenberg 1968, Power & Devine 1970).

During the late Cretaceous the Rolling Downs

* School of Applied Science, Canberra College of Advanced Education, Canberra, A.C.T. 2616.

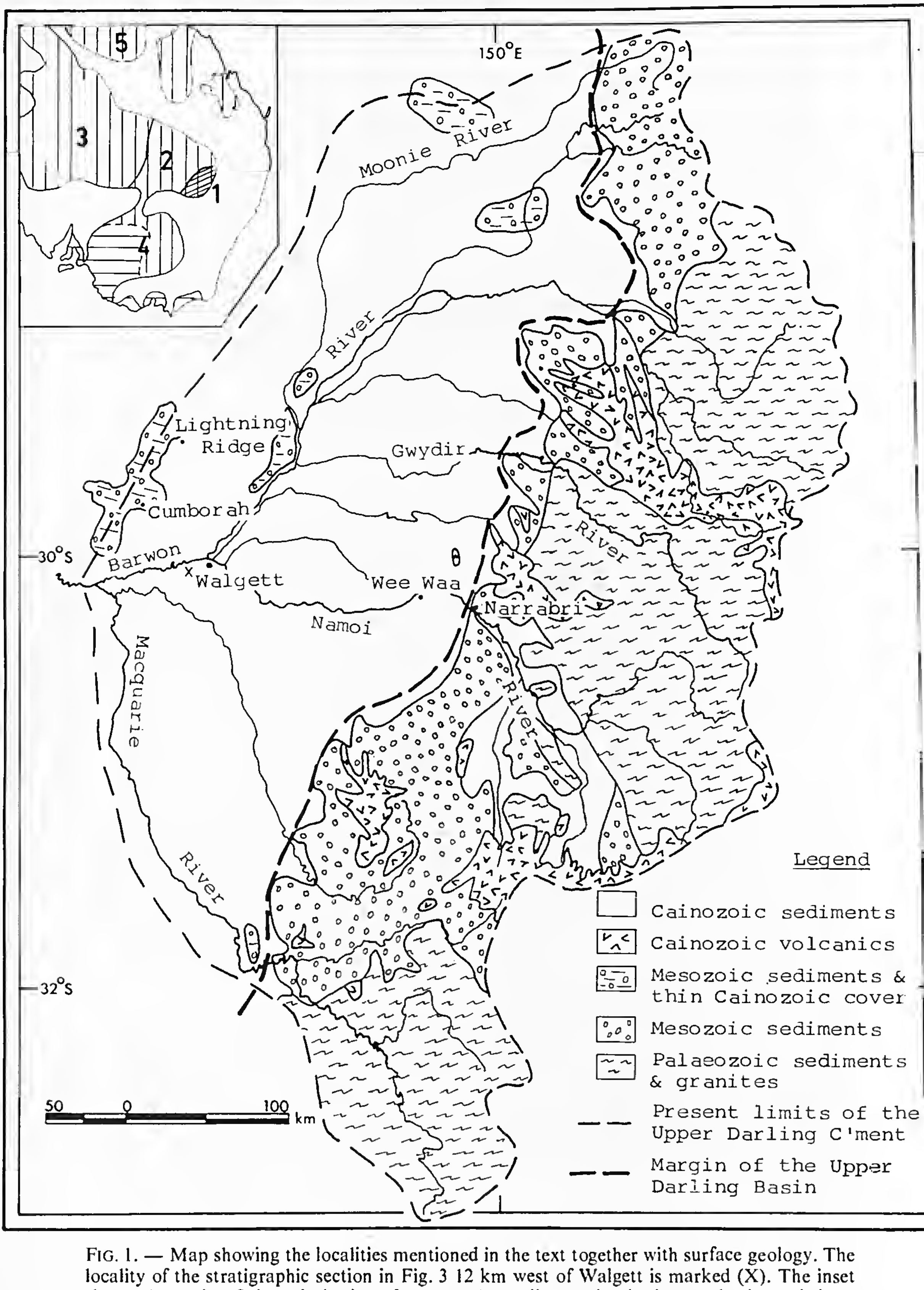

FIG. 1. — Map showing the localities mentioned in the text together with surface geology. The locality of the stratigraphic section in Fig. 3 12 km west of Walgett is marked (X). The inset shows the major Cainozoic basins of eastern Australia; marine basins are horizontal lines, terrestrial are vertical. 1. Upper Darling Basin; 2. Darling Warrego Basin (Brown *et al.* 1968); 3. Eyre Basin; 4. Murray Basin; 5. Karumba Basin.

Group was exposed to weathering and erosion by uplifts along the eastern margin of the Basin (Wellman 1971). Senior *et al.* (1968), B. Senior (1972), D. Senior (1972, 1973), Idnurm and Senior (1978) and Taylor (1976, 1978) all discuss the weathering of the Rolling Downs Group. The rocks were intensely weathered to depths of up to 100 m, forming weathering profiles dominated by kaolinite and quartz with occasional ironstone concretions and bands near the surface. This weathering phase culminated with the formation of silcretes and ferruginous crusts in the early Eocene (Idnurm & Senior op. cit.). In the Cumborah-Walgett Region this silcrete is identifiable over large areas of Cretaceous outcrop and is called the Llanillo Silcrete (Taylor 1978).

The Llanillo Silcrete is a silicified horizon at or near the top of the weathering zone developed in the Rolling Downs Group. Unlike its equivalents in southeastern Queensland (Senior 1972) it is not associated with the ferruginous nodules and ironstone crusts dated by Idnurm and Senior op. cit. Taylor (1976) however considers it to be of the same age, i.e. early Eocene. Wellman (1971) showed that during the late Cretaceous-early Tertiary the eastern highlands of the New England region were uplifted some 800 m.

For the period from the formation of the Llanillo silcrete to the Miocene there is no record of deposition in the western two thirds of the Upper Darling Basin. However, in the easternmost section of the Basin, Martin (1973) records Eocene to late Miocene pollen at depths up to 107 m (Fig. 2). Deposition during the early Tertiary was restricted to the eastern portion of the Basin suggesting that, at least for some of the early Tertiary, palaeoslopes were still towards the east over the greater part of the Basin or that this early sedimentation was restricted by the change in gradient to a belt proximal to the eastern highlands. Fig. 2 shows that if the latter was the case then a downwarp of some 40 m in the Narrabri-Wee Waa region must have occurred post-Eocene.

A sheet gravel, the Cumborah Gravel (Taylor 1972) unconformably overlies the Llanillo Silcrete and the deeply weathered Cretaceous sediments on the ridges in the Lightning Ridge-Cumborah area, and is present also under the more recent fluvial sediments in the Walgett region. These gravels contain chert, quartz, jasper and silicified wood fragments which originated from the Jurassic sediments flanking the western margins of the eastern highland. They also contain clasts of weathered Rolling Downs Group sediment and fragments of the Llanillo Silcrete. The gravels attain a maximum thickness of 5 m but are generally less than 1 m.

The presence of these gravels indicates a change in the palaeoslope and hence some Basin tectonism between the Eocene and when they were deposited. This change in palaeoslope between the Eocene and the deposition of the Cumborah Gravel is the time of origin of the Darling valley as it is today. The age of the Cumborah Gravels is unknown except that they post-date the Eocene and pre-date the oldest fluvial valley fill of late Pliocene age.

The top of the Cumborah Gravel has been silicified to form the Mt. Charlotte Silcrete (Taylor 1976). This silcrete is not associated with ironstones or laterites but does represent a second and less intense phase of weathering in the Basin. Idnurm and Senior (1978) also record a second phase, which they date at late Oligocene, in southwestern Queensland. This Oligocene event is not related to that which produced the Mt. Charlotte Silcrete but Senior (pers. com.) records a third silicification event in central Queensland which in all probability does correlate with the Mt. Charlotte Silcrete.

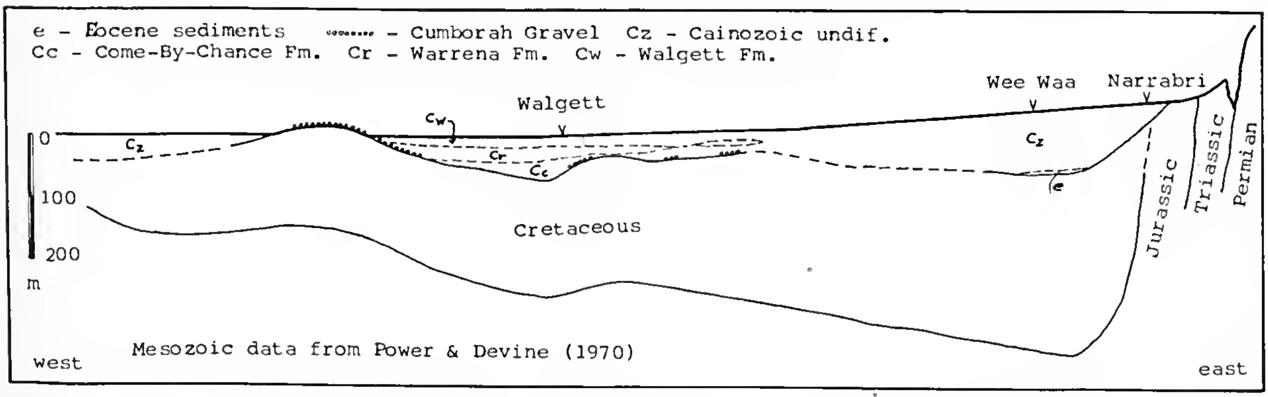

FIG. 2. — Section across the Upper Darling Basin from east to west through Walgett and Narrabri.

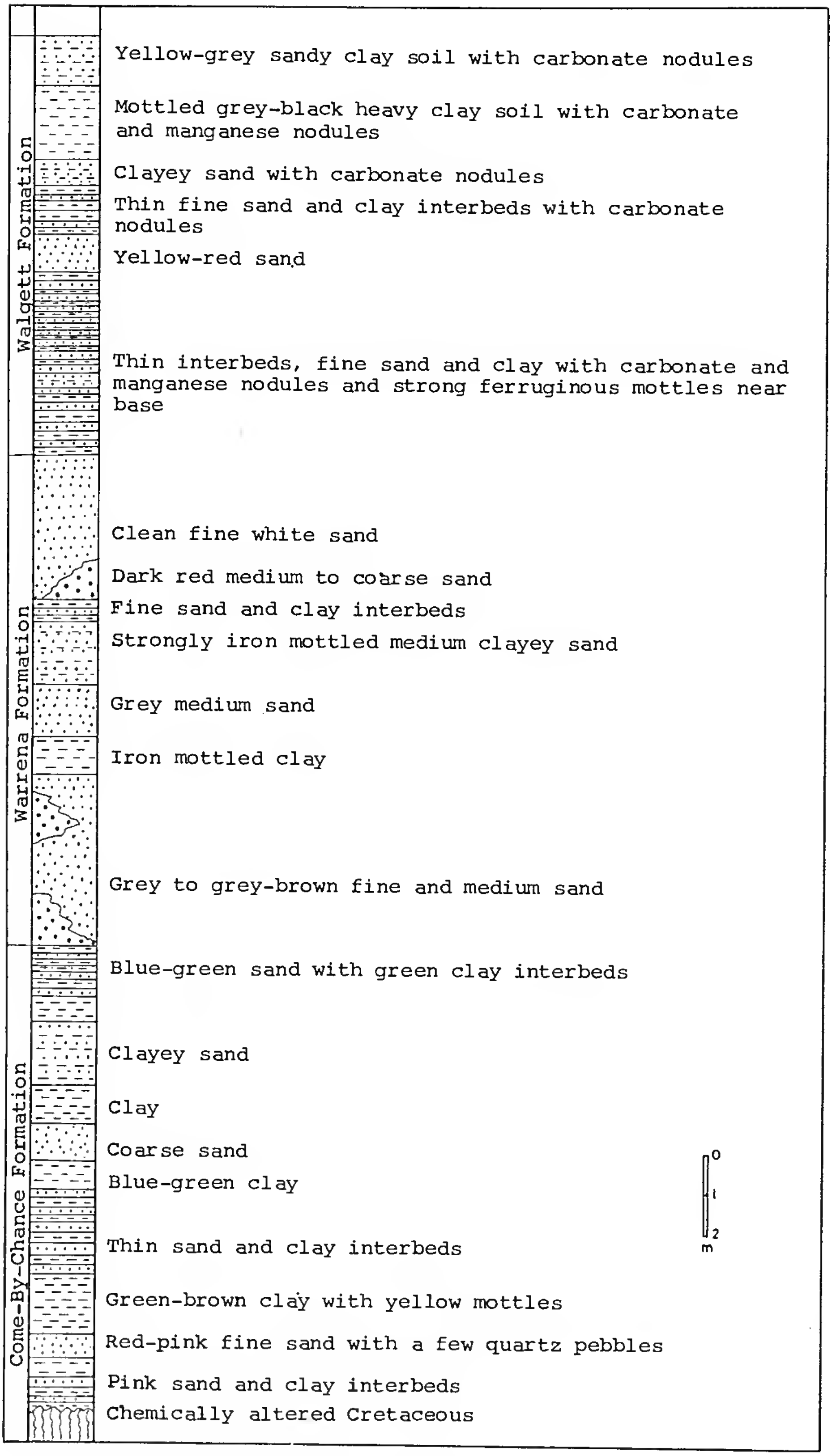

FIG. 3. — A log of the Cainozoic sequence from 12 km west of Walgett. Bore site is marked (X) on Fig. 1.

LATE TERTIARY TO RECENT

During the late Pliocene or early Pleistocene the eastern highlands were uplifted some 200 m (Wellman 1971). As with the earlier vertical tectonism in the eastern source regions this movement too was accompanied by gentle folding and some faulting in the Basin. It is this movement which folded the Cumborah Gravel and faulted it; at Mt. Charlotte the Cumborah Gravel is down-faulted against the Llanillo Silcrete and deeply weathered Rolling Downs Group.

It was during this period, Pliocene to Recent, that the 50 m or so of fluvial deposits accumulated in the greater part of the Upper Darling Basin. Offenberg (1968) and Brunker (1967, 1968) report some 120 m of 'Cainozoic undifferentiated' in the Upper Darling Basin. With the exception of the area along the eastern Basin margin where Eocene sediments occur, the greatest depth of fluvial sediments recorded by the present author is 60 m near Walgett. The thicker sequences in this area noted by previous authors are taken to result from their failure to recognise the thick weathered zone on top of the Rolling Downs Group.

Three formations have been recognised in the Basin-fill (Fig. 3). The oldest is the Come-By-Chance Formation. This unit unconformably overlies the Cumborah Gravel or the deeply weathered Rolling Downs Group. It is overlain, apparently conformably, by the Warrena Formation. The Come-By-Chance Formation is an interbedded sequence of muds and sands up to 19 m thick. The basal portions contain reworked Cumborah Gravel; the remainder consists of interbeds of fine to medium sub-feldsic sands and kaolinitic muds. A sample from 4.5 m above the formation base yielded late Pliocene pollen (Dr. J. Owen, pers. comm.).

The Come-By-Chance Formation is coarser to the northeast of Walgett and finer toward the southwest and west, suggesting that the depositing rivers flowed in similar patterns to those of today.

The Warrena Formation is about 12 m thick in the central area of the Basin and is essentially a medium sand. The sands are dominantly quartzose with up to 5% feldspar. The clay minerals from thin clay partings and beds (Fig. 3) are kaolinitic towards the base of the unit, becoming more montmorillonitic towards the top. The uppermost 1-2 m of the sequence is strongly pedogenised in some areas, suggesting the overlying Walgett Formation is disconformable.

The age of the Warrena Formation is unknown although, using approximate sedimentation rates, it is estimated to be Pleistocene. The formation is restricted in its distribution to the northern and central areas of the Basin and the depositing streams flowed from north and northeast to the west. The morphological character of the depositing streams is unknown, although they were substantially different from the present Darling (Riley & Taylor 1978). The Warrena Formation is a fluvial sheet sand similar in many respects to those discussed by Veevers and Rundle (1976).

The Walgett Formation averages 10 m thickness. It is a muddy unit composed dominantly of pedogenised montmorillonitic clays with minor amounts of sand (*c.* 95% quartz and 5% feldspar). This unit represents the 'flood basin' deposits of the present rivers in the central regions of the Basin. It is cut through by palaeochannels which have associated with them a sandy phase and a later muddy phase. These two phases are separated out as the Vauxhall and Barokaville Formations respectively. The Walgett Formation is overlain around the Basin margins by coarser grained units deposited by the modern streams (Riley & Taylor 1978).

DISCUSSION

It is possible that a warm, humid climate was required for the formation of the deep weathering profile on the Rolling Downs Group and a warm, humid but seasonal climate for the production of silcretes (Goudie 1973). Kemp (1978) shows that there were major changes in the Cainozoic climates in southeastern Australia, partly as a result of changes in ocean temperature and partly from the northerly drift of Australia from Antarctica. Ocean temperatures were warm from the Palaeocene to early Oligocene (Shackleton & Kennett 1975) and resulted in warm, humid continental climates reported by Kemp (1978) from examination of the floral assemblages from that period. The floral evidence suggests widespread areas of rainforest during the Palaeocene, Eocene and early Oligocene with rainforest giving way to more open forest in the late Oligocene. After the early Oligocene ocean surface temperatures decreased irregularly throughout the remainder of the Tertiary with two brief reversions of about 3° in the early Miocene. By the late Miocene the polar ice cap expanded and sea temperatures reached a low of about 4°. This resulted in a relatively arid phase on the continent and the change from forests to open grasslands.

The climatic and floral history is generally consistent with the known stratigraphy of the Upper Darling Basin. The deep weathering and lack of thick sediment bodies in the early Cainozoic could indicate warm humid climates and a

landscape dominated by rainforest and/or forest vegetation. Several authors (Ruxton 1967, Wilson 1969, Fouriner 1949) have shown that there is significant sediment production in tropical rainforests. Langbein and Schumm (1958) have shown that while sediment is produced it is about one third that produced in more temperate climates. The majority of the material in the deeply weathered profiles preserved in both the eastern highlands and the Basin is dominated by clay sized components. This being so the size of the available material would allow it to be flushed through the system leaving only the coarser detritus in the Basin or catchment areas. It is however difficult to imagine the development of the Cumborah Gravel under warm-humid climates with forest vegetation. If the Mt. Charlotte Silcrete correlates with the second, late Oligocene, weathering phase (Canaway Profile of Idnurm & Senior 1978) this means the Cumborah Gravel was formed in a forested basin. This style of deposit is more in keeping with deposition under less densely vegetated arid to semi-arid conditions. Such conditions first occurred during the late Miocene.

There was a brief but distinct warming and associated increase in humidity during the early Pliocene, accompanied by the return of rainforest. It is during this phase, the present author suggests, that the Mt. Charlotte Silcrete developed in the Cumborah Gravel. This early Pliocene warming and rainforest resurgence is also reflected by the lack of any early Pliocene sediments.

If the equivalent of the late Oligocene Canaway Profile occurs in the Upper Darling Basin it has not been recognised or is inseparable from the early Eocene profile.

In the late Pliocene two significant events occurred in the Basin. The eastern source areas were uplifted and the climate changed from warm and humid to cooler, drier, less stable climates with alternately arid and more humid phases. As a result of these changes production of sediment from the eastern highlands increased and deposition of the three thick fluvial sequences in the Basin began. The detailed relation between the climatic events of the late Tertiary to Recent and the changes in style of fluvial deposition are unknown although some comments on the most recent changes are made by Riley and Taylor (1978).

The systematic change in clay mineralogy through the fluvial sequence reflects the change in the nature of the detritus formed in the provenance. The lower part of the sequence, rich in kaolinite was presumably derived from the thick early Tertiary weathering profiles of which relics are still preserved under Oligocene to Miocene basalt flows in places (Crook 1961), and from the late Tertiary weathering profiles of the basalts.

Once these kaolinitic profiles were stripped the eroded material became increasingly rich in montmorillonite as a result of weathering under climatic conditions more arid or similar to the present (Craig & Loughnan 1964).

CORRELATIONS

Table 1 is a correlation chart for some of the major Cainozoic Basins in eastern Australia, from the Karumba Basin to the Murray Basin. The correlations attained are relatively good and demonstrate the widespread nature of Cainozoic events in eastern Australia. Some of the major features include:

1. The widespread Cretaceous to early Eocene weathering and associated duricrusts throughout northern and central areas of eastern Australia.
2. The general absence of any depositional activity over wide areas of continental eastern Australia from the Eocene to Miocene, with the exception of deposition in marginal marine and internal drainage areas.
3. The extensive deposition of relatively thin sheet conglomerates and sands during the Miocene or late Miocene.
4. The widespread early to mid-Pliocene weathering event.
5. The very widespread development of continental fluvial sedimentation during the mid-Pliocene to Recent.

The synchroneity of these events over such a wide area of eastern Australia is remarkable and suggests extensive uniformity of climate and/or tectonism during the Cainozoic in eastern Australia. There is reasonable evidence (Wellman 1971) for widespread synchroneity of tectonic events throughout the Cainozoic in southeastern Australia. Independent evidence from northeastern Australia is more localised but supports the evidence of Wellman. The Cainozoic climatic history for southeastern Australia is relatively well known but the northeastern Australian climates for the same period are only poorly known. The correlations discussed here however suggest that the gross climatic variations were similar throughout eastern Australia during the Cainozoic.

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TABLE 1

VICTORIAN MURRAY BASIN (2) Lawrence 1976 Gill 1973	MURRAY BASIN, EAST (2) Woolley & Williams 1977 and Woolley 1978	LACHLAN VALLEY (3) Williamson 1969	AGE	UPPER DARLING BASIN (4) Taylor 1976	EROMANGA BASIN (5) Senior (in Doutch 1976) Idnurm & Senior (in press)	KARUMBA BASIN (6) (Platform Segment only) Doutch 1976
Coonambidgal Fm. *fluvial*	Shepparton Fm. *fluvial*	Cowra Fm. *fluvial*	HOLOCENE	Barokaville Fm. Vauxhall Fm. Walgett Fm.	*younger river deposits*	*younger fluvial and fan deposits*
WIDGELLI PEDODERM		? ? ?		? ?	? ? ? ?	HOLROYD SURFACE *aeolian deposits*
Shepparton Fm. *fluvial* KAROONDA SURFACE XX		? ?	PLEISTOCENE	Warrena Fm. *fluvial* ? ? Come-By-Chance Fm. *fluvial*	*older river deposits*	*older Clara, Gilbert & Mitchell fan deposits*
Parilla Sand *marginal marine* Bookpurnong Beds *marine*	Calivil Fm. *fluvial*	Lachlan Fm. *fluvial* ? ? ? ?	PLIOCENE Late Early	MT CHARLOTTE XX SILCRETE XX	? ? ?	
Calivil Fm. *fluvial* Torrum-barry clay		Glenlogan Gravel *fluvial* ? ? ?	MIOCENE Late Mid	Cumborah Gravel *fluvial*	Glendower Fm. *fluvial* ? ? ? Etadunna Fm. *fluvial*	Wyabba Beds *continental & marine*
MURRAY GP. *marine carbonate deposition*			Early		? ? XX CANAWAY PROFILE ++ CURALIE SILCRETE ? ?	
Olney Fm. *deltaic tidal & lagoonal*	Olney Fm. *fluvial & ? marginal marine*		OLIGOCENE Late Early	*fluvial deposition in east*	Eyre Fm. *fluvial*	
Warina Sand *fluvial* ? ? ?	Warina Sand *fluvial*		EOCENE Late Early			
			PALAEOCENE Late Early	XX LLANILLO SILCRETE	+ MORNEY PROFILE +	
			CRETACEOUS Late Early	ROLLING DOWNS GROUP	ROLLING DOWNS GROUP	Bulimba Fm.

X Silcrete
+ Ironstone

to use material presently in press. Dr. N. O. Jones critically reviewed the manuscript.

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6

CAINOZOIC SEDIMENTATION IN THE MURRAY DRAINAGE BASIN, NEW SOUTH WALES SECTION

By D. R. WOOLLEY*

ABSTRACT: Geological evolution of the drainage basin began in Eocene time with commencement of sedimentation in the Murray Basin. The initial phase consisted of widespread deposition under terrestrial conditions, including some sedimentation of embayments in the valley margin which appear to mark the location of the forerunners of the Murrumbidgee and Lachlan Rivers. During a marine transgression from the southwest, which persisted from Oligocene to Pliocene time, terrestrial deposition was restricted to the eastern marginal parts of the Basin. Erosion of the present Murrumbidgee and Lachlan valleys in the eastern highlands occurred mainly during late Pliocene and Pleistocene time. The history of the Murray Valley upstream from Corowa is similar to that of the Lachlan and Murrumbidgee, but it joined a northward extension of the Ovens River prior to the late Pleistocene when it linked with the Goulburn River drainage system. Sand and gravel lenses within some of the Tertiary formations constitute an important aquifer system, from which can be obtained supplies of low salinity water sufficient for irrigation and municipal purposes.

INTRODUCTION

The area referred to in this paper includes the drainage basins of the Lachlan and Murrumbidgee Rivers, and the N.S.W. part of the Murray and Lower Murray drainage basins, as defined by the Australian Water Resources Council (1976). Aspects of the Cainozoic geology within other parts of the Murray-Darling System are described by Taylor (1978) who refers to the Darling drainage basin, and Macumber (1978) who describes the Victorian part of the Murray drainage basin.

Much of the new information on which conclusions in this paper are based has been obtained as a result of investigations into groundwater resources of the area by the Water Resources Commission of N.S.W. The Tertiary sequence contains several very important aquifers, and groundwater within the study area is of economic importance both as a source of water for irrigation and municipal water supplies and because of its effects on surface hydrology. A brief statement on groundwater occurrence has therefore been incorporated.

The geological evolution of the Murray-Darling drainage system can be regarded as having commenced in early Tertiary time with the beginning of deposition of sediments in the Murray Basin. This structure is a sedimentary basin of some 300,000 km^2 extent in Victoria, New South Wales and South Australia. Of this 135,000 km^2 are in N.S.W. It was initiated by movement along major lineaments and fracture zones during Early Permian and to a lesser extent Jurassic-Early Cretaceous time (Scheibner 1974), and subsidence continued during the Cainozoic while active sedimentation was taking place (Pels 1969). At the commencement of Tertiary sedimentation, the land surface consisted of Palaeozoic rocks around the margins, with Palaeozoic, Permian, Cretaceous and Triassic units exposed in the Basin floor area. Contours on this pre-Tertiary surface are shown in Fig. 1. The Tertiary stratigraphy of the New South Wales part of the Basin has been described by Woolley and Williams (1977), and is summarised by the cross section in Fig. 2.

CAINOZOIC GEOLOGY AND STRATIGRAPHY

The first phase of sedimentation in N.S.W. is represented by the mid- to late-Eocene Warina Sand (Lawrence 1972) which was deposited under generally non-marine conditions, and consists of medium to coarse grained quartz sand with minor dark grey clay lenses and carbonaceous layers. It is restricted to the deepest parts of the Basin, and in New South Wales does not occur east of Hay. The

* Water Resources Commission of New South Wales, Box 952, P.O., North Sydney, N.S.W. 2060.

overlying unit is the Olney Formation (Lawrence 1972) which was deposited under deltaic, fluvial, lagoonal and tidal-flat environments, and is dominated by lignite layers up to several tens of metres thick. It also contains grey carbonaceous clay and extensive sand lenses, and occurs throughout the Basin. In the southwestern part of N.S.W. its age is late Eocene, but in the eastern part of the Basin it ranges up to early Miocene. These ages, and most others quoted below, are based on the palynological studies of Martin (1973, 1977, pers. com.).

Sediments of Eocene age which can be referred to the Olney Formation occur in a narrow valley for a few km upstream from the margin of the Murray Basin at Narrandera. This long narrow embayment into the highland area flanking the Eocene plain is the earliest recognisable stage of the Murrumbidgee River system. A similar embayment appears to have been present east of Hillston representing the earliest stage of the Lachlan River, but dating of the deposits in this locality is less certain. There is no known comparable feature related to the Murray River which did not adopt its present course until much later, but similar features have been noted by Macumber (op. cit.), notably for the Goulburn River.

During early Oligocene time a marine transgression commenced from the southwest and resulted in deposition of the Ettrick Marl above the Olney Formation in southwestern N.S.W. This grades to the east into a glauconitic and dolomitic clay (Geera Clay, Lawrence 1966) which in turn grades laterally into the middle parts of the Olney Formation. The Olney Formation represents terrestrial deposition around the Basin margin, concurrent with marine deposition in the shallow sea to the west.

The area subject to marine conditions reached a maximum during Miocene time, but the sea did not extend much further east than Balranald. From early to mid-Miocene the Duddo Limestone was deposited in the southwest of N.S.W., with its landward equivalent the Winnambool Formation. The latter is represented by siltstone, sandy clay and dolomite in N.S.W. and grades to the east (landward) into the upper part of the Olney Formation, its terrestrial equivalent. There was a period of non-deposition in the eastern part of the Basin during the mid-Miocene and presumably a slight regression of the sea, but marine deposition was continuous. Rivers draining the highlands to the east and north of the Basin and the swampy areas bounding the Miocene sea were the forebears of the present Murray-Darling System.

There is some depositional evidence of a river system in the highland area dating from this time and valley erosion is assumed to have been more or less continuous until the late Oligocene (Wellman & McDougall 1974). The embayments at Hillston and Narrandera persisted from Eocene time, but there is a long gap between the upstream limit of Miocene sedimentation in them, and comparable material in the main highlands. The high level Glen Logan Gravel which occurs within the present Lachlan Valley around Cowra is considered to be of Miocene age (Williamson 1964) and represents the earliest phase of deposition in the highland part of that valley. More definite dating is available for early Miocene fluvial and lacustrine deposits up to 300 m thick in the Snowy Mountain area (Owen 1975), and for early Pliocene basalt which partly infills valleys in the same area and overlies the lacustrine material (Wellman & McDougall op. cit.). Some of these localities are within the present Murray/Murrumbidgee drainage system, but their relationship to the drainage system of the early Miocene is not clear. Climate of the time was warm and humid, with an annual rainfall of 1500-1800 mm near Wagga Wagga (Martin 1977) slightly less than during the Oligocene when the annual rainfall is estimated to have exceeded 1800 mm (Martin op. cit.).

Terrestrial deposition around the Basin margin recommenced in the late Miocene with deposition of the Calivil Formation (Macumber 1973) which continued until early Pliocene time. This formation is dominated by coarse quartz sand and gravel, particularly in the Basin margin areas. It represents the initial phase of erosion associated with the post mid-Miocene uplift of 200 m (Wellman & McDougall op. cit.) which can be identified with the Kosciusko uplift (Browne 1969). The proportion of clay increases towards the centre of the Basin. It grades into and partly overlies the Bookpurnong Beds, which consist of pyritic siltstone and sandstone grading westwards to glauconitic sand deposited during the final phase of marine transgression. The coarse grain size of the Calivil Formation probably reflects the first movements of the Kosciusko Uplift, during which the present valleys of the Murrumbidgee, Lachlan, and Murray Rivers were further entrenched into the Palaeozoic terrain to the north and east of the Murray Basin.

At this stage, there was still no Murray River as we now know it. The river draining the Murray

Valley of the eastern highlands left its present course just north of Corowa and flowed in a west-northwesterly direction to join with the north-flowing Ovens River. This drainage system is indicated by the distribution of alluvial deposits upstream of Corowa and by bedrock contours in the Ovens Valley shown by Macumber (1978, Fig. 1). Additional evidence is provided by bedrock contours north of the Murray River and west of Corowa (Fig. 1), and by the apparent absence of sediments older than Pleistocene in the shallow alluvial-filled gap at Mulwala (midway between Tocumwal and Corowa, Fig. 1).

In Pliocene time, rainfall began to increase (Martin 1973) and final regression of the sea had commenced, resulting in deposition of shoreline deposits of the Parilla Sand. Terrestrial deposition around the eastern margin of the Basin was mainly fluvial and comprised the silt, clay, and minor sand of the Shepparton Formation (Lawrence 1975). Aggradation of the eroded valleys of the Murrumbidgee, Lachlan and Murray Rivers, and probably also of the Darling, commenced. These sediments, referred to the Lachlan Formation (Williamson 1964), are dominated by pale grey quartz gravels and grey clays which may be carbonaceous. Rainforest was widespread at this time, particularly in the eastern part of the drainage system.There was apparently a decrease in annual rainfall from the eastern highlands to the west, with over 1800 mm at Wagga Wagga and less than 1500 mm at Hay (Martin 1973).

During the Pleistocene Period, rainfall decreased substantially, to the extent that the rainforest disappeared from much of the catchment. This correlates with, and may have been an important causal factor of, a change in the type of sediment supplied to the river system as erosion progressed rapidly without the protective forest vegetation. Polymictic gravels, generally quite coarse, are widespread in the shallower parts of the alluvial fill of the main valley systems deposited under this regime (Kalf & Woolley 1977). They are interbedded with brown fluvial clay and sandy clay deposits, in a depositional unit referred to as the Cowra Formation (Williamson 1964).

West of the highlands, the present Riverine Plain was formed during this period by the action of distributory and aggrading prior streams (Butler 1950). The prior stream sands are the plains equivalent of the gravels of the Cowra Formation.

It seems likely that a major change in the Murray-Ovens-Goulburn drainage system took place during late Pleistocene time. The north-flowing Ovens, joined near Corowa by the Murray, changed its course to flow west and link with the Goulburn. This initiated the present day Murray River System as 'a westerly flowing connector linking the northerly and northwesterly flowing (Victorian) tributary systems' (Macumber 1978). Subsequent evolution of this river system is beyond the scope of this paper but has been examined by a number of authors (e.g. Pels 1966).

OCCURRENCE OF GROUNDWATER

Groundwater occurs extensively within the Cainozoic sediments, and the following formations are particularly favourable:

Warina Sand: This is the basal stratigraphic unit within the Cainozoic sequence, and does not occur east of the latitude of Hay. It is an important source of water for stock, but except in a small area near the eastern limit of its extent the salinity of its water exceeds 1000 mg/l which is unsuitable for irrigation or municipal uses. Water salinity increases towards the west, to about 4000 mg/l near Balranald and higher west of there. The formation has a high transmissivity (400-2000 m^2/d from limited tests), indicating that high yields would be available.

Olney Formation: This unit contains extensive sand and gravel lenses, particularly in the alluvial fan area west of Narrandera (located near Bore 25394, Fig. 1) where they are coarse grained and thick. Very high transmissivity values (800-6000 m^2/d) have been obtained in this area, where a number of high yielding (100 to 300 l/s) bores are used for irrigation. The usefulness of the aquifer decreases towards the west because of increasing water salinity and a smaller proportion of sand and gravel lenses within the formation. Water having a salinity of less than 1000 mg/l occurs within a zone between the Lachlan River and Willandra Creek, with a western limit at about the latitude of Booligal, and also in a zone mainly south of the Murrumbidgee River extending west nearly to Hay. There is a further zone between Tocumwal and Deniliquin, less well delineated, in which the aquifers also contain low salinity water. West of these areas the salinity increases rapidly (10,000 mg/l at Balranald).

Calivil Formation: The major water-bearing sand and gravel lenses in this Formation are also located in the alluvial fan west of Narrandera, where high yielding bores used for irrigation obtain part or all of their supply from them. The distribution of water salinity within the unit is comparable to that in the Olney Formation, but the sand and

FIG. 1 — Contours on pre-Tertiary surface, Murray Basin.

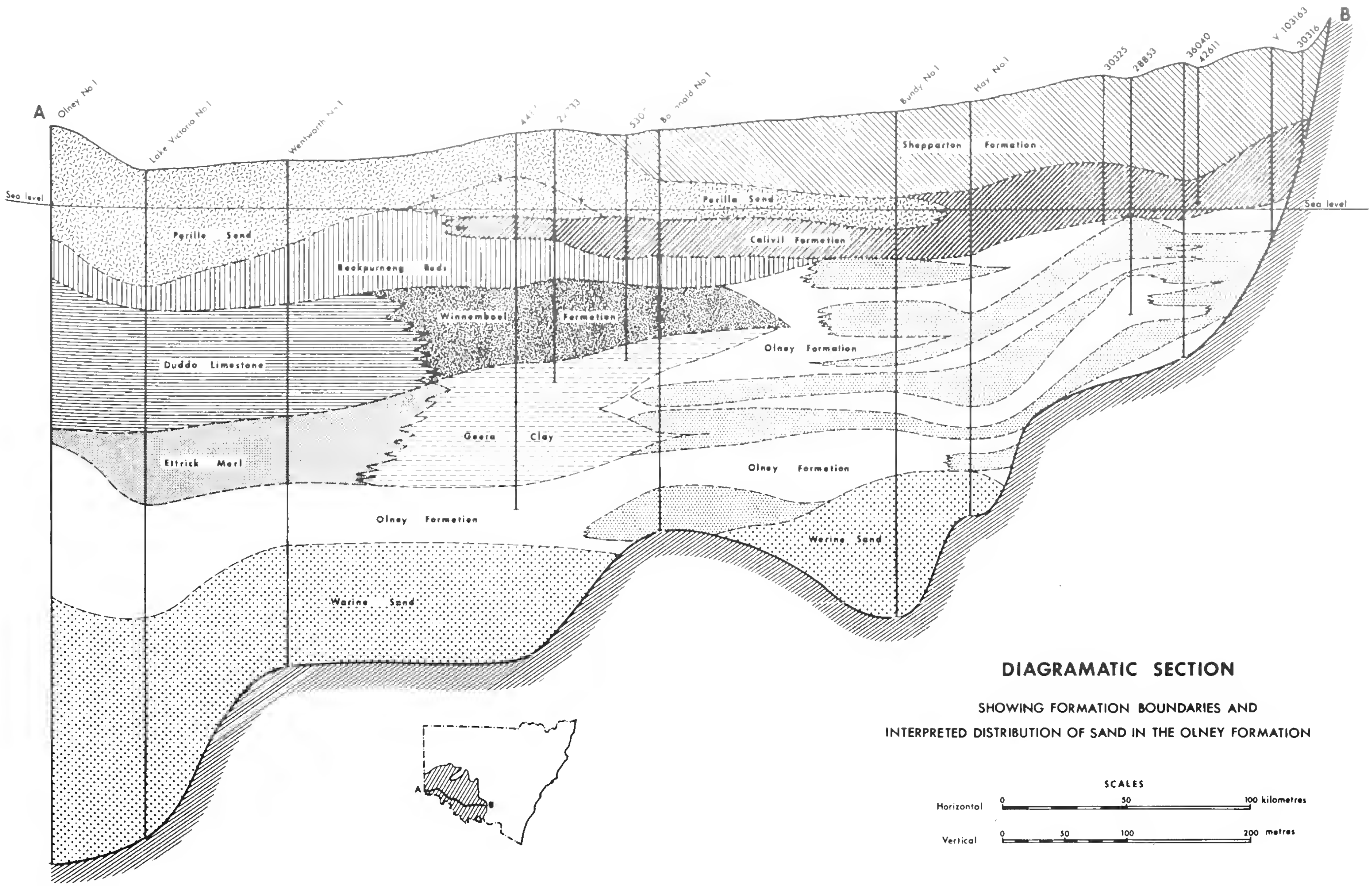
A
B
Olney No 1
Lake Victoria No 1
Wentworth No 1
Bundy No 1
Hay No 1
30325
28853
36040
42611
V 103163
30316
Sea level
Sea level
Shepparton Formation
Parilla Sand
Parilla Sand
Calivil Formation
Bookpurnong Beds
Winnambool Formation
Duddo Limestone
Olney Formation
Geera Clay
Ettrick Marl
Olney Formation
Olney Formation
Warina Sand
Warina Sand
A
B
DIAGRAMATIC SECTION
SHOWING FORMATION BOUNDARIES AND
INTERPRETED DISTRIBUTION OF SAND IN THE OLNEY FORMATION
SCALES
Horizontal
0 50 100 kilometres
Vertical
0 50 100 200 metres

FIG. 2

gravel lenses which provide the aquifers are less extensive than those in the Olney Formation.

Lachlan Formation: This unit occurs within the valley section of the Lachlan, Murrumbidgee and Murray Rivers, upstream respectively of Hillston, Narrandera and Corowa, and is a major source of groundwater. Low salinity water from it is used for both irrigation and town water supply in the Lachlan Valley upstream of Condobolin, and in the Murrumbidgee Valley. Transmissivity values are commonly in the range 500-1500 m^2/d and individual bores yield up to 200 l/s.

Recharge to these aquifers occurs mainly along the major rivers within the alluvial valleys and for a relatively small distance across the Riverine Plain: for example for some 80 km along the Murrumbidgee River west of Narrandera. In these recharge areas, salinity of the groundwater is low and the hydraulic head in the shallower aquifers is higher than the head in the deeper aquifers. This distribution of head results in an overall downward movement of water. Outside the recharge areas, the head in the deeper aquifers is higher than that in the shallower acquifers, resulting in an overall upward movement of groundwater. Since the salinity of groundwater in these discharge areas is relatively high, particularly in the shallower aquifers, further investigation of the inter-relationships between groundwater and surface water regimes is warranted.

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7

RIVER MURRAY FLOOD FLOW PATTERNS AND GEOMORPHIC TRACTS

By D. T. CURREY* and D. J. DOLE*

ABSTRACT: During severe floods, as in 1974 and 1975, large volumes of water leave the River Murray on the Victorian and New South Wales sides. A flood flow of 200,000 Ml/d* in the river at Tocumwal can reduce to 30,000 Ml/d in the river at Barmah, and 200,000 Ml/d in the lower Goulburn can reduce to 30,000 Ml/d at Swan Hill. Variations in flood plain dimensions reflect the magnitudes of overflows from various lengths of the river. The modern course of the river traverses parts of the ancestral flood plains of its tributaries, and part of the Riverine Plain. By reference to these older features, five river tracts can be distinguished in sequence from the highlands above Corowa to the Mallee below the Murrumbidgee junction.

* Ml = 1,000,000 litres = approx. 0.8 ac. ft
Gl = 1,000 Ml
Ml/d = approx. 0.4 cusecs

FLOODS AND FLOOD PLAINS

River Murray levels have been recorded at Echuca Wharf since September 1865. From May 1906 permanent gauges were established along the river, and flood records from them show that the river was in flood throughout its length during 1870, 1916-17, 1956 and 1973-75, and that in other years localised flooding occurred depending on which tributaries were in flood.

In the past, flood discharge records and recorded flow patterns, together with analysis of characteristics of the river and its flood plain have been used as the basic information for the design of levees at the most suitable locations to minimize flood damage. Early attempts to levee the River Murray were approached with caution since it was well recognised that both the flood hydrology and the geomorphology of the flood plain were complex. In 1921 an interstate committee (New South Wales & Victoria) recommended criteria for the consideration of further flood protection and reclamation works. These criteria were developed taking into consideration that in the event of a flood of the magnitude of 1917, the volumes of active flood pondage were 2,000 Gl in New South Wales and 700 Gl in Victoria; the average depth in Victoria was about 1 m whilst in New South Wales it was only 0.5 m. In considering future strategies it is of interest to note that the analysts of the day (1921) computed that the effect of a complete leveeing of the main Murray channel would be to raise the flood level at Swan Hill by some 7.5 m. The significance of this extreme approach was not lost; the cost of these works was seen as 'absolutely prohibitive whilst the resulting menace to the land at present free from submergence would be very serious and absolutely unjustified'.

Current analysis aims at establishing the reasons for flood flow patterns so that flood plain management guidelines can be formulated for planning in the future. This is essential because of the flat gradients traversed by the river. The gradient of the plain is 1:5,000 so that usually insignificant land forms such as natural river levees, up to 1 m high, have a significant effect on flood flow paths and cause extensive sheets of water to become ponded behind them.

Broadly, flow patterns show that the flood waters are retained within the flood plain above Corowa and below Boundary Bend, but in between the water overflows onto the Riverine Plain. An extreme instance is the situation that has arisen on several occasions at Barmah where the effect of flood inflows from the Goulburn River has been to reverse the hydraulic gradient to the extent that flow at Barmah actually reverses. This is illustrated by the peak discharge chart of the May 1974 flood (Fig. 1). Peak flow passing Tocumwal was

*State Rivers and Water Supply Commission of Victoria, 590 Orrong Road, Armadale, Victoria 3143.

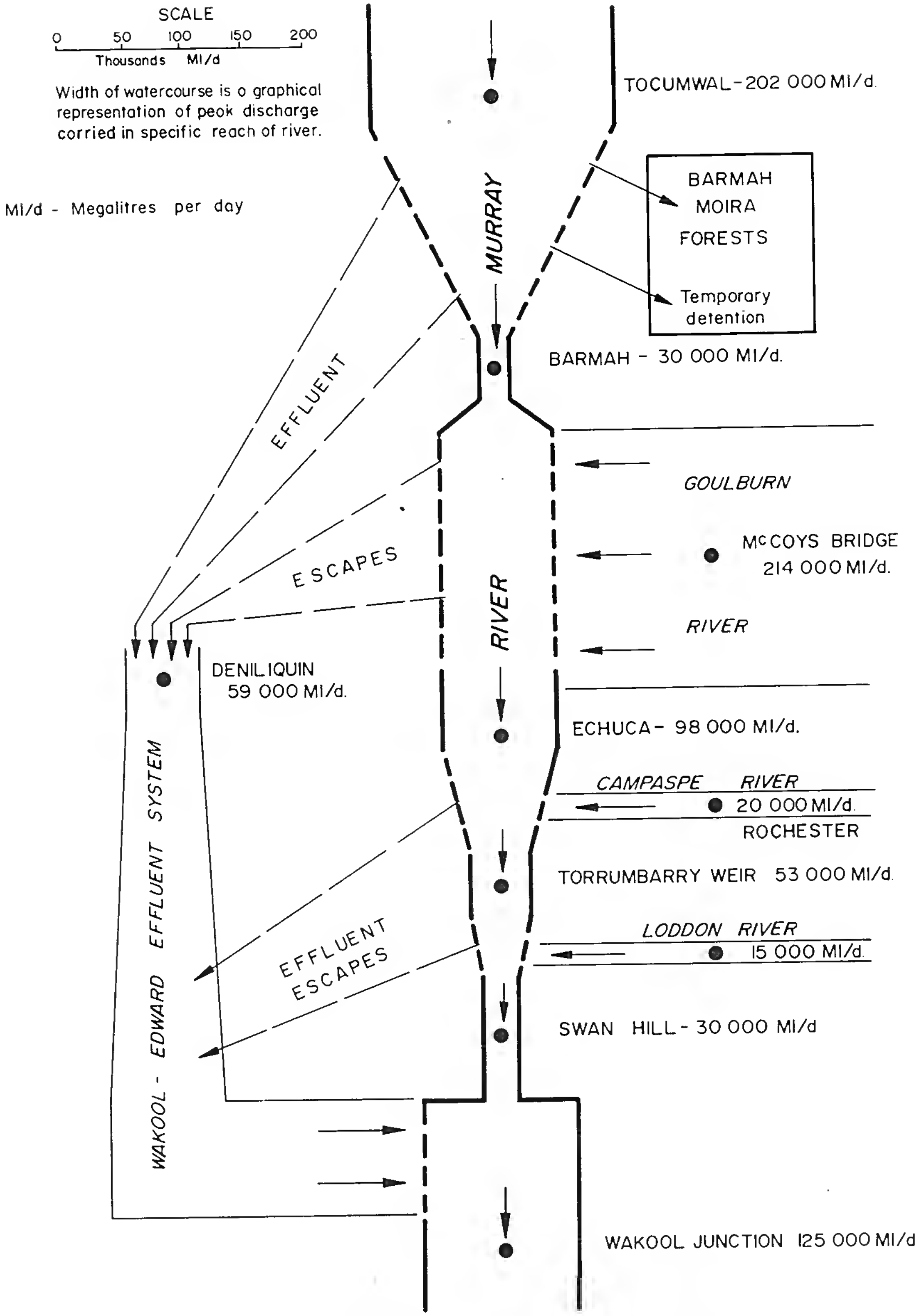

FIG. 1 — River Murray, tributaries and effluents. Peak discharges during the May 1974 Flood.

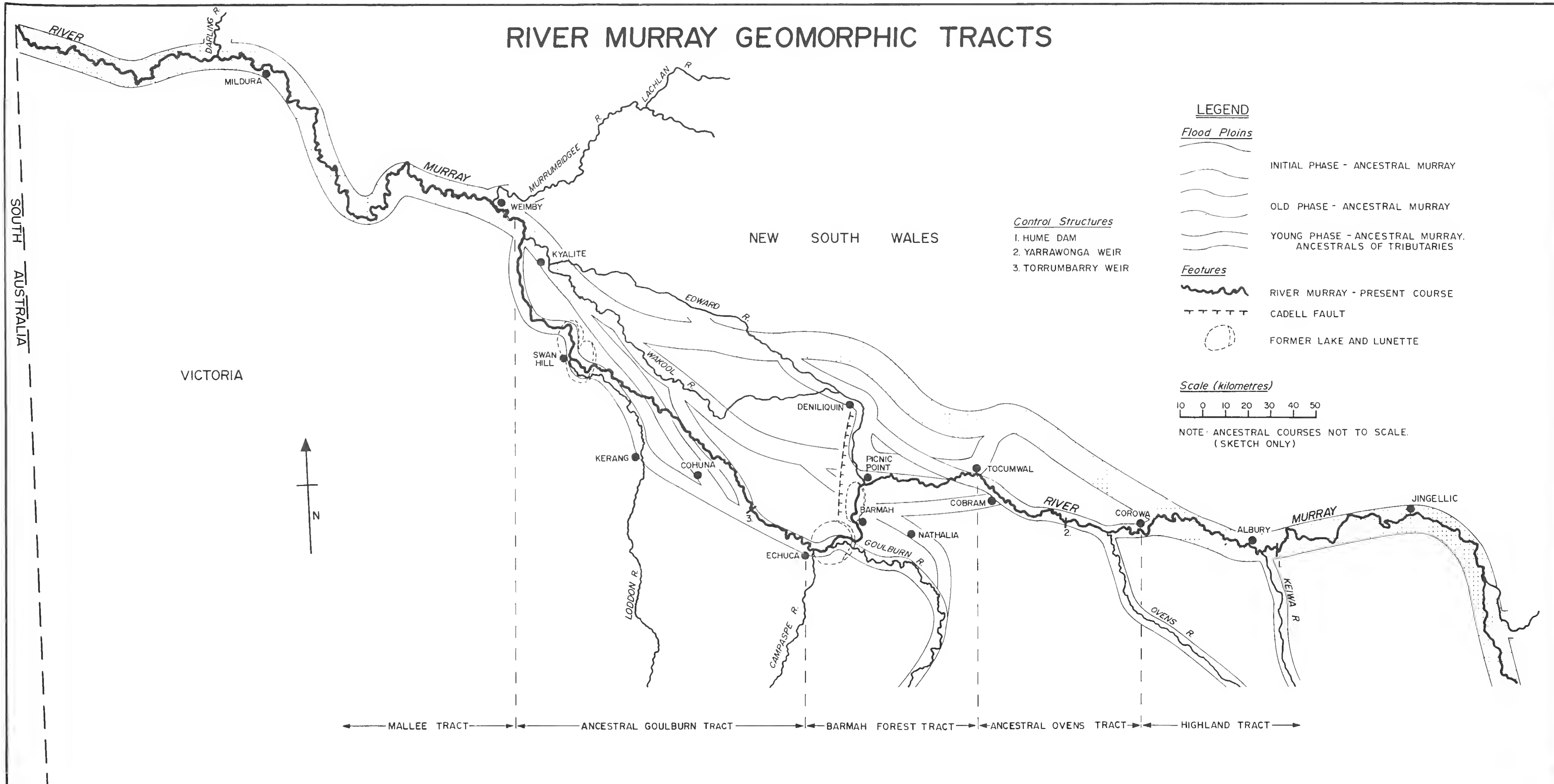

Fig. 2 — River Murray tracts showing ancestral courses of the river system.

202,000 Ml/d but downstream at Barmah was only 30,000 Ml/d because the water had overflowed either into the Barmah Forest or the Edward River. The reason for this flow behaviour becomes evident when the relationship between the past and present drainage systems are recognized.

The former courses of the Murray's immediate precursors, the ancestrals, were first described and mapped by Pels (1964), and since then geologists have mapped the ancestors of the tributaries. Pels showed that 'following the final depositional phase of prior streams (Butler 1950), a phase of large-scale incision occurred and resulted in a system of deep wide channels across the plain'. Also he demonstrated that there were three distinct phases before the present Murray established its course. Although the sequence of ancestral Murray flood plains can be clearly defined, they will be labelled as either old or young when describing their relationship with the present flood flow paths.

The purpose of this paper is to demonstrate the controlling effect of the ancestral tracts on flood discharge behaviour, thus providing example of the control exerted between Quaternary geological evolution and the modern hydrologic regime. The valuable contributions by Pels and Bowler in describing these ancient systems allows an understanding of past hydrologic history which bears directly on modern river management. Practical use can be made of their work in hydrology flood studies for levee design and for predicting trouble spots along the river, as well as in adding to the basic data needed for the future management of the flood plain.

By super-imposing the flood patterns on their geomorphic maps it is evident that depending on where the Murray is today with respect to the ancestral flood plain system it can be divided into ancestral tracts, as these control the flood pattern.

The term flood plain will be used in the descriptions of the various ancestral systems, and in this paper the river is said to possess a flood plain when it is flowing in an alluvial belt of country lying slightly below the surrounding plain. This best represents deposits of the present or earlier phases of river development. In this sense the flood plains represent the upper surface of bodies of alluvium inset into the plain. When no such inset relationship occurs, as when the river is not associated with any particular ancestral course but may be cutting across earlier channel traces, the river is said to lack any associated flood plain.

ANCESTRAL TRACTS

Detailed geomorphic mapping from aerial photographs, soil maps, contour plans, and field studies has enabled us to trace the system of river channel evolution (Fig. 2). Although this agrees well with maps produced by Pels (1966) and Bowler-Harford (1966) it differs in one respect in that we include one channel system in the history of the Murray evolution that predates that which Pels referred to as ancestral river Phase I, the Green Gully Phase. The Green Gully Phase followed this older system and broke out of it at Tocumwal. However, Pels (1966) described the lower end of this older system and named it the Tulla River Branch. He stated that the Tulla Branch shows that 'Coonambidgal I sediments were re-excavated during this phase (Coonambidgal II). Residuals now remain as terrace remnants along the sectors of the river where the two phases are super-imposed' The Goulburn was a tributary of Green Gully and it also followed an earlier phase along the Tallygaroopna system, with similar older terrace remnants. Therefore our suggestion questions the validity of Bowler's (1966) naming of the Tallygaroopna system as a prior stream. This involves instead a large Murray system, which leaves the Murray at Corowa and flows west passing north of Deniliquin. Its surface blends in with the general level of the plain approximately 10 m above the Murray flood plain, and it is flanked by sand dunes along its length. Furthermore, the 30 m thickness of sand and gravel infilling the ancestral valley is abruptly terminated at Corowa, and the flood plain is eroded in Riverine clays downstream from that point. This can be explained if the infilled valley followed the suggested course north of Corowa.

In the terminology of Pels (1964) and Butler (1950) this early system may be termed a prior stream. In the sense in which we are using the term it constitutes one of the early ancestral courses of the present day Murray. Also the early ancestral courses of the Goulburn are revealed when the aeolian material is artificially removed from the Tallygaroopna system. A false impression is given by the wind blown sand, that the Tallygaroopna is of the prior stream raised type of topography, but, as shown in Fig. 3, it is revealed as an ancestral type incised below the plain.

Pels had the ancestral systems dated and named them Coonambidgal I, age exceeding 28,600 years; Coonambidgal II, age 26,200 to 13,400 and Coonambidgal III, age 9,800 years. The present course is 9,000 years old (Bowler, pers. com.). Bowler's (1966) date of the Tallygaroopna N306-20,300, coincides with the Coonambidgal II age. Subsequent bores have proven this stratigraphically, and in addition that gravel beds below belong to Coon-

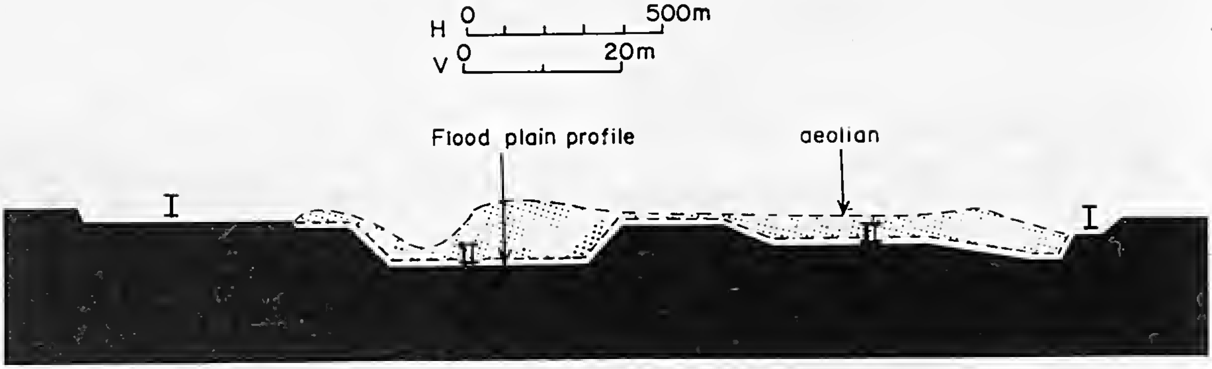

FIG. 3 — Tallygaroopna system — ancestral Goulburn. Aeolian sand covers Coonambidgal I and II flood plains. (Parish Tallygaroopna, Lot 30.)

ambidgal I, as previously argued by Pels. The complication to the Green Gully system is due to its disruption by the Cadell Fault during the early stages of Coonambidgal II development. It continued as the diverted Murray named Gulpa Creek (Pels 1964) and the diverted Goulburn named Kotupna (Bowler 1966).

The older ancestrals of the Murray were diverted north by the Cadell Fault, past Deniliquin into the Wakool System, which is the downstream end of the disrupted Green Gully System. Later the younger ancestrals eroded a gap at Corowa into the old and younger ancestral Ovens flood plains. The old Ovens continued west past Cobram to join the Tallygaroopna-Goulburn near Barmah. The younger Ovens-Murray continued to Tocumwal, formed the Bullatale and joined the old Murray at Deniliquin. The Tallygaroopna was defeated by the fault but survived as the Kotupna system (late Coonambidgal II) which eroded a gap in the Barma sand hills, crossed the Kanyapella lake floor and flowed west, past Echuca. It branched at Cohuna: one course entered the Wakool-old Murray system, and the other course continued past Kerang, crossed a lake floor at Swan Hill and returned to the old Murray system at the Wakool Junction.

RIVER TRACTS

The dimensions and features of the River Murray flood plain change rapidly after the river leaves its oldest ancestral flood plain at Corowa (Fig. 4). It occupies, in turn, the ancestral Ovens flood plain, the Moira-Kanyapella lake system and the ancestral Goulburn flood plain before returning to its oldest ancestor at the Wakool River junction, in the Mallee. In total there are five distinct tracts along the New South Wales-Victorian border. These have been named to correspond with the geomorphic history of each tract (Fig. 2) as the:

Highland Murray Tract, from the headwaters to Corowa.
Ancestral Ovens Tract, Corowa to Tocumwal.
Barmah Forest Tract, Tocumwal to the Goulburn River.
Ancestral Goulburn Tract, Goulburn River to the Wakool River.
Mallee Tract, downstream from Wakool River.

The tracts are highlighted by the graphical representations of the flood peak discharges, May 1974 (Fig. 1) and October-December 1975 (Fig. 5). The 1974 record shows discharges between Tocumwal and Wakool Junction and the 1975 record from Jingellic (New South Wales) to Blanchetown (South Australia).

HIGHLAND TRACT

The headwaters of the River Murray are in the Great Dividing Range where the river and tributaries flow in steep narrow valleys. Floods in these reaches of the Murray rise rapidly to peaks and subside almost as quickly, and are confined to the flood plain. An example of the rapid rise and fall was the flash flood in March 1964, on Copabella Creek, a tributary at Jingellic. A peak flow of 60,000 Ml/d from a catchment area of only 250 km^2 occurred about two hours after an extremely heavy thunderstorm concentrated over a small area. This peak was attenuated (flattened out) as it passed downstream, to 44,000 Ml/d in the Copabella at Jingellic and 34,000 Ml/d in the Murray two km further downstream. Even without the effect of Hume Dam, a localised flood of this nature would have had no great effect below Albury. The significance of flash flooding is evident when compared with the 1975 Murray flood peak discharge at Jingellic, which was 126,000 Ml/d from a catchment area of 6,527 km^2 (Table 1). The

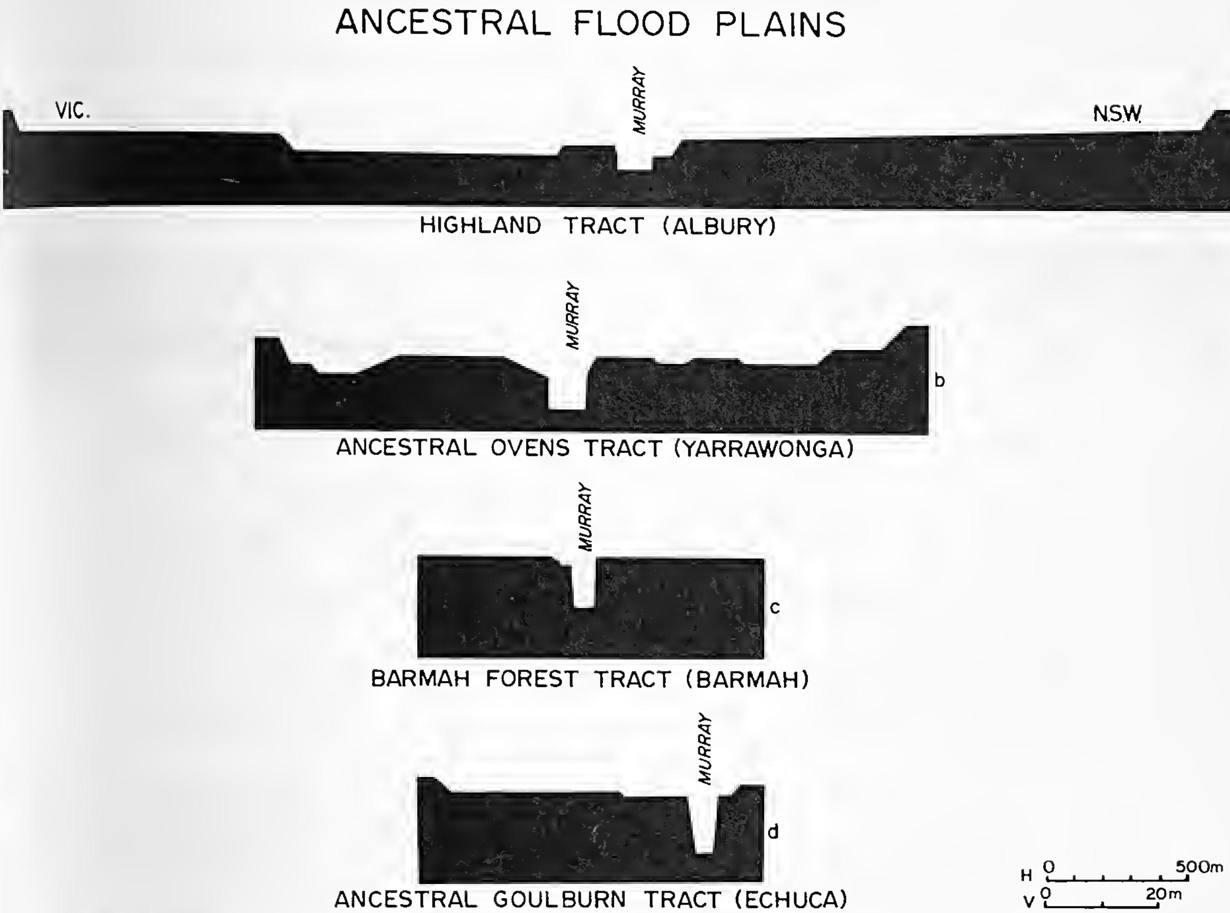

FIG. 4 — Flood plain sections of the tracts. Comparison between the dimensions shows the flood retention capabilities of each.
Note. — The River Murray flood plain dimensions decrease downstream from Albury. Beyond Wakool dimensions increase.

discharge had increased to 163,000 Ml/d at Albury.

The Highland tract is continuous from the Murray headwaters to the township of Corowa, a length of 450 km. The tract retains the flood plain remnants from all of its ancestors (Fig. 4a), as far as Corowa where the younger ancestral flood plains, 10 m below, leave the older.

Tributary valleys contain the same components as the main stream. These were briefly described by Rowe (1967, 1972) as 'mature valleys with broad alluvial flats and raised terraces'. The flood plain extends the full width across the valley, often abutting against bedrock. River channel meanders are angular, separating relatively straight reaches of river. The river's channel is shallow and wide, often more than 150 m. Banks consist of sand and gravel whilst cobbles are common on the bed. A typical section at Jingellic, 100 km upstream from Albury, shows these features. Ancestral river flood plains and terraces have been formed over the deep lead gravels, which infill the valley to 70 m. Here the flood plain extends across the entire river valley with modern point-bars inset within adjacent older alluvial sediments.

At the downstream end of the tract, near Corowa, the flood plain widens and is marked by numerous abandoned river channels and meander scrolls. The river bed and banks are in sandy materials and these deposits extend to 30 m below the river bed.

Ancestral Ovens Tract

The River Murray leaves the foothills and bedrock outcrops at Corowa and enters the Riverine Plain. At Corowa the flood plain narrows as the river leaves its older ancestral flood plain and erodes through a narrow gap to connect with the

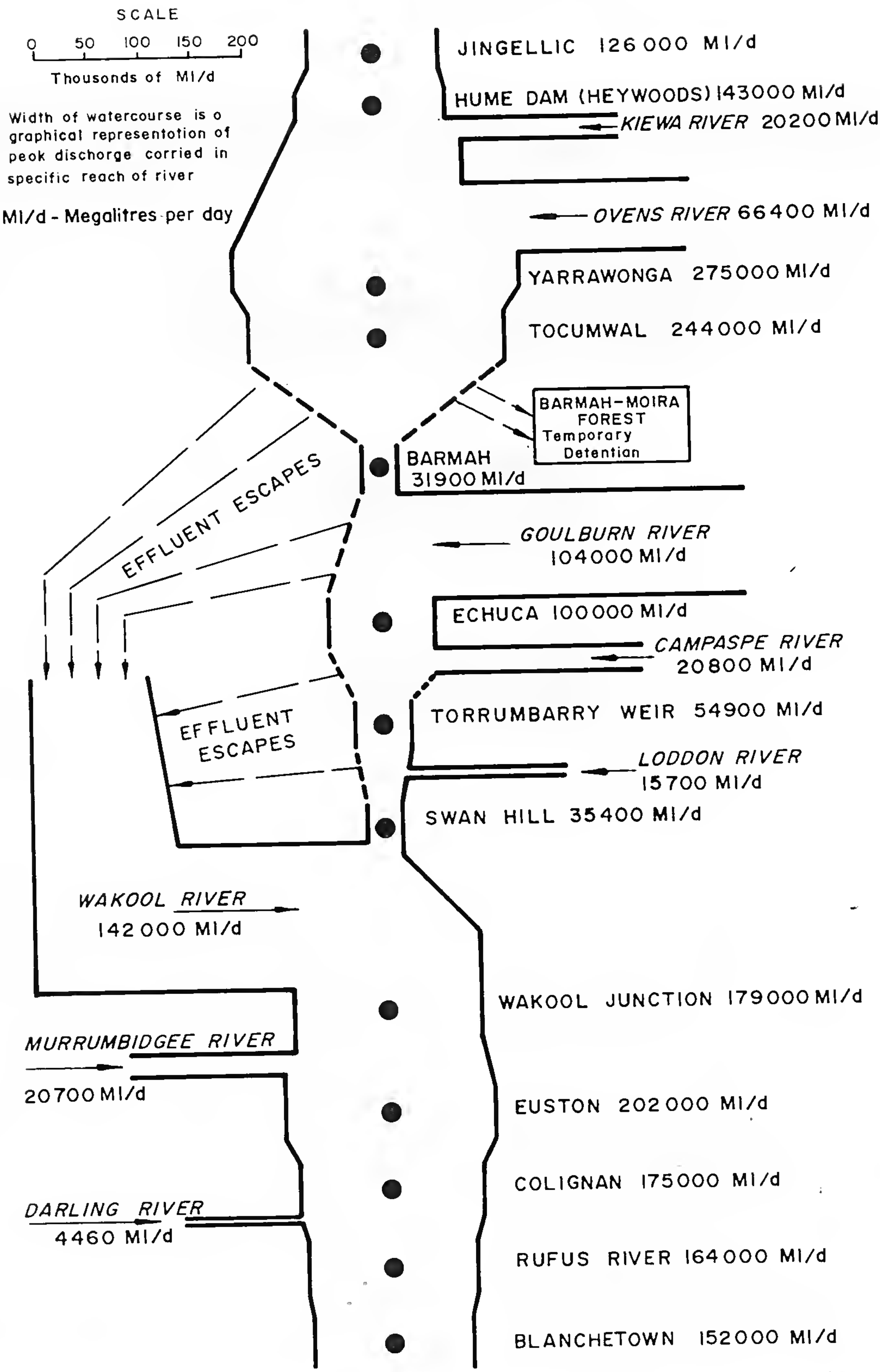

FIG. 5 — River Murray, tributaries and effluents. Peak discharges during the October-December 1975 Flood.

TABLE 1
RANGE OF DISCHARGES—VARIOUS STATIONS.

Stream	Station	Catchment Area km^2	Maximum Annual Discharge		Minimum Annual Discharge		Mean Annual Discharge over Period of Record		
			Year	Discharge Gl	Year	Discharge Gl	Period	Discharge Gl	Depth mm
Murray	Jingellic	6 527	1917-18	6140	1902-03	677	1890-1970	2374	364
Mitta	Tallandoon	4 716	1917-18	4268	1902-03	250	1886-1970	1415	300
Kiewa	Kiewa	1 145	1917-18	2077	1914-15	166	1886-1970	634	554
Ovens	Wangaratta	5 411	1917-18	4924	1902-03	174	1887-1940	1444	267
Goulburn	Murchison	10 772	1917-18	7390	1940-41	146	1882-1970	2145	199
Campaspe	Elmore	3 398	1956-57	823	1944-45	0.8	1886-1964	237	70
Loddon	Laanecoorie	4 178	1893-94	743	1944-45	9.3	1891-1966	231	55
Condamine —Maranoa		87 000	1950	6660	1923	8.1		1050	12
Macintyre Basin		37 200	1950	4320	1940	100		875	24

Note: Figures are actual flows. No account is taken of diversions or storage construction during period of record.

ancestral Ovens flood plains. The sediments and terraces of the Ovens River were described by Newell (1970). The river remains in the ancestral Ovens tract, as far as Cobram, where it leaves the older Ovens to follow its younger ancestral flood plain to Tocumwal.

The whole discharge from a Murray flood passes along the present river course to Tocumwal. Flood peaks at Yarrawonga are influenced by the Ovens and Murray peaks, which may or may not be coincident. Major flood peaks occurring during prolonged periods of high flow are not significantly attenuated along this reach of the river: for example peaks in the 1975 flood (Fig. 5) were:

Outflow from Hume Dam	143,000 Ml/d
Kiewa River	20,200 Ml/d
Ovens River	66,400 Ml/d
Total	229,699 Ml/d

Peak outflow from Yarrawonga Weir was 275,000 Ml/d which approximates the sum of the inflows when unmeasured inflows from minor upstream tributaries are included.

Significant pondage of floodwater occurs on the flood plain between Hume and Yarrawonga, and in smaller floods, and outside periods of prolonged high flows some attenuation of peaks is evident. A flood peak will usually take two to three days to pass from Hume to Yarrawonga and a further day to reach Tocumwal (Table 2).

During the disastrous floods of 1917 substantial areas in Victoria between Cobram and Barmah were flooded because of flood breakaways from the river. Following these floods a comprehensive system of levees was constructed along the Victorian side. The October 1975 flood, which was of similar magnitude to the 1917 event, breached these levees in a number of locations below Cobram, including sections at their connections with sand dunes. The breakaway water flowed westerly along a former major river course (old Ovens) overland towards Barmah and in the process caused substantial flooding on its former flood plain.

The ancestral Ovens tract, between Corowa and Tocumwal, a distance of 90 km, contains the older ancestral flood plains of the Ovens River and the younger ancestral flood plains of the River Murray (Fig. 4b). The older ancestral section in this tract can accommodate the flood flows; however, the succeeding ancestral sections become progressively smaller, and at Cobram leave the older flood plains. Flood overflows occur along the older flood plain to the west as flows become restricted by the smaller, younger flood plain immediately to the north. The flood plain below Corowa is 3.2 km wide and consists of terraces etched in the Riverine Plain clay

TABLE 2
PEAK DISCHARGES — 1975 FLOODS.

Station	Peak Discharge Ml/d	Date
Jingellic	125 900	26/10
Hume (Heywoods)	143 000	27/10
Yarrawonga	275 000	29/10
Tocumwal	244 400	30/10
Barmah	31 900	2/11
Echuca	100 300	4/11
Torrumbarry	54 900	3/11
Swan Hill	35 400	15/11
Wakool Junction	179 000	23/11
Euston	202 300	25/11
Colignan	175 000	30/11
D/S Rufus River	163 800	14/12
Blanchetown (Lock 1)	151 700 (Est.)	17/12
Kiewa River	20 200	26/10
Ovens at Wangaratta	66 400	26/10
Goulburn at McCoys	103 900	29/10
Campaspe at Rochester	20 800	26/10
Loddon at Highway Bridge	15 700	1/11
Murrumbidgee at Balranald	20 700	31/10
Darling at Burtundy	4 460	14/12
Wakool at Kyalite	141 800	18/11

sediments. The modern river meanders sinuously over the flood plain, sometimes following but often out of phase with inherited ancestral meanders. Moreover, compared with the river in the upstream tract, the modern channel is relatively deep and narrow.

BARMAH FOREST TRACT

The dominating flow path feature of the Barmah Forest Tract is the Edward-Wakool effluent system, which receives the greater part of the river flow during major floods. For example during three months October-December 1975 some 55% of the total volumes passing Tocumwal overflowed into the ancestral river courses in New South Wales, to join the Edward River at Deniliquin.

In this tract, between Tocumwal and the Goulburn River junction, flows frequently exceed the river channel capacity of about 11,000 Ml/d and spread out to cover the forest floor. Flood overflows into the Edward River may be caused either by direct flood flows or by the effects from floods in the Goulburn and Campaspe systems forcing the Murray waters to back up, and in

extreme instances around Barmah, to reverse the normal direction of flow.

The ease with which flooding can occur or change direction is due to the absence of flood plains in this tract (Fig. 4c). The river is limited in capacity, with a maximum channel capacity in relevant sections of around 11,000 Ml/d. This results in overflow into the adjacent lake and swamp formations. Even during major Murray floods, the peak flow through a restricted section known as the Barmah Choke does not exceed 30,000-35,000 Ml/d, although flows past Tocumwal may exceed 200,000 Ml/d. These flows are significantly reduced by backwater effects of Goulburn flows which enter downstream. On at least two occasions this century during peak flood conditions the hydraulic gradient has been reversed and the Murray has flowed north through Barmah. Spills on the Victorian side into the Barmah Forest return to the main river upstream of Barmah so the forest in this case serves as a detention pondage. On the north side the spills pass to the Edward-Wakool system and eventually return to the River Murray at Wakool Junction. The flow paths are illustrated by the 1974 and 1975 charts (Figs. 1 & 5).

The distribution of major flood flows in this tract (Fig. 5) shows that a peak flow of 275,000 Ml/d at Yarrawonga resulted in a peak flow of only 31,900 Ml/d at Barmah. The remaining floodwaters escaped to the Edward-Wakool system. The additional contribution from the Lower Goulburn of some 104,000 Ml/d resulted in a peak flow of only 100,000 Ml/d at Echuca. Similarly during the 1974 flood (Fig. 1) the peak flows recorded at Barmah and Echuca were 30,000 Ml/d and 98,000 Ml/d respectively, even though the corresponding flood peaks at Tocumwal and in the Lower Goulburn were, respectively, 202,000 Ml/d and 214,000 Ml/d.

The behaviour of the flood flow paths can be attributed to the land forms established in this tract before and after faulting impeded the westerly flow of the River Murray. Harris (1939) suggested that 'changes were effected by a number of displacements' on the Cadell Fault. The old ancestrals of the Murray were disrupted and caused to flow along the Gulpa Creek at the toe of the fault escarpment to Deniliquin (Pels 1966). Later the younger ancestrals followed the old for a short distance beyond Tocumwal, left them and formed the Bullatale Creek flood plain. During these river changes Lake Kanyapella and the Moira lakes were formed.

The present river broke away from the ancestral flood plains downstream from Tocumwal and formed a new channel beside the old ancestral Murray to Picnic Point. It has breached a lunette, and turned south across the Moira Lake floor to Barmah. The river eroded through the Riverine Plain at Barmah, continued south and broke through the Barma sand hills to flow west across the former Lake Kanyapella floor to the Goulburn River. These landforms and the history of formation were described by Bowler and Harford (1966) and later in more detail by Bowler (1970).

The meander belt is narrow, 150 m, and the meander wave lengths are less than 1,000 m. The modern channel is less than 75 m wide and is cut to a depth greater than 15 m. The bed of the channel is composed predominantly of fine sand, and its banks of clay.

The Ancestral Goulburn Tract

The River Murray enters the ancestral Goulburn flood plain on the floor of the former Lake Kanyapella, upstream of Echuca. From this location to the Wakool junction the river breaks out of the ancestral Goulburn course at Torrumbarry and returns to it at Swan Hill.

Flood flow patterns continue to be influenced by the lake floor systems in the upper portion of this tract. The effect at Echuca of coincident flood flows in the Campaspe River is of major importance. A coincident Campaspe flood produces a backwater effect in the Murray at the township, and it is this backwater effect superimposed on a flood in the Murray-Goulburn system which causes a significant rise in flood levels at Echuca. In 1870 and in 1916 the increase in flood level as a result of the impact of the Campaspe was 1 m and 1.5 m respectively. Eventually a level is reached at which water escapes to New South Wales over a long stretch of bank downstream of Echuca and this probably occurred during the highest recorded flood in 1870.

From Echuca to Wakool Junction the flood plain section is still very limited (Fig. 4d) and further escapes to the Edward-Wakool system occur at many places between Torrumbarry Weir and Swan Hill. On the Victorian side, although major overflows near Torrumbarry have been controlled by levees, substantial volumes of water flow into the Gunbower-Koondrook forest (including along an ancestral course passing towards Kerang). From Torrumbarry to Swan Hill levees have been constructed along both sides of the river. However they are still at levels which result in their being overtopped in major floods. This allows water to flow up and along its ancestral flood plains in some sections, and onto the Riverine Plain in others.

The flood plain capacity at Swan Hill is of the same order as at Barmah (a peak of 35,400 Ml/d was recorded in 1975) so during a sizeable flood, escapes to New South Wales will be equivalent to the whole of the input from the Goulburn, Campaspe and Loddon Rivers.

Analysis of the flood period May-October 1974 and October-December 1975 shows that only 30% of the total flow entering the Murray below Tocumwal actually passed Swan Hill. The remainder is either held in pondage in the former lakes or conveyed through the ancestral courses in New South Wales to return to the River Murray at Wakool.

The flood flow paths coincide with either the Goulburn's various ancestral flood plains which are not occupied by the Murray or with the Murray course on the Riverine Plain. The river follows the older ancestral Goulburn to Torrumbarry and then flows north along the younger ancestrals. The old ancestrals continue west and divide near Cohuna, one arm forming the Gunbower Creek which passes north-west through Koondrook to the Wakool River. The other arm turns north at Kerang with the Loddon River, crosses a lake floor at Swan Hill, and joins the Wakool-Edward system to the north.

The Murray leaves the younger ancestral courses north of Cohuna, crosses the Gunbower arm at Koondrook and rejoins the older ancestral at the Loddon River junction behind a lunette, upstream from Swan Hill. It then enters the Mallee and remains in the ancestral Goulburn flood plain until it rejoins its own older ancestral flood plain at Wakool River junction.

The morphology of the Murray in this tract changes along its length. From Echuca to Torrumbarry, 95 km, it is similar to the Goulburn flood plain, which has large meander scrolls, terraces and sand dunes on its surface. The modern channel is deeply incised, 15 m, with a sandy bed, and a meander pattern controlled by the larger ancestral meanders on the flood plain. There is a reduction to the younger ancestral flood plain dimensions downstream from Torrumbarry, and the modern river channel has sinuous, small, irregular wave lengths, less than 900 m. The channel is less than 100 m wide, and the meander scroll remnants and flood plains are absent. After it enters the ancestral Goulburn at the Loddon River junction, the channel widens and deepens, and the meander scrolls reappear on the flood plain.

Mallee Tract

Downstream from the Edward-Wakool system the whole of the Murray flood flows are retained within its ancestral flood plain, below the Mallee surface. The magnitude of flood peaks in the Mallee Tract is considerably attenuated in the Edward-Wakool system which, during major floods, forms a vast temporary lake of some 5,000 Gl capacity. The Murrumbidgee River joins the Murray below Wakool Junction and adds its influence downstream. The magnitude of flood peaks for both the Murrumbidgee and the Darling in the October-December 1975 period was small in comparison to the individual peaks recorded in these systems.

At Wentworth the Murray is joined by the Darling River, which has its headwaters in Queensland and northern New South Wales. The Upper Darling is subject more to summer rainfall than the Murray, and Murray and Darling floods are not usually coincident. The largest floods downstream of Wentworth are produced when floods from the two rivers happen to coincide, as in 1956. Darling River flows are variable, and annual discharge at Menindie has ranged from 13,700 Gl in 1890 to a mere 1.2 Gl in 1902. Below the Darling there is no further contribution to the flow of the River Murray except in high floods along the great Anabranch of the Darling.

The combined ancestral flood plains of the Murray-Murrumbidgee, 10 km wide, retain the largest floods. They are marked by terraces, abandoned channels, ancestral river meander scrolls and irregular sand dunes. The river channel is 16 m deep and it is wider than the channel in the ancestral Goulburn Tract.

CONCLUSIONS

River Murray flood flows and flow patterns change dramatically along the length of the river. Large volumes which escape from the river are either temporarily ponded in former lakes or swamps or return hundreds of km downstream along flood plains formerly occupied by ancestors of the present river system. The retention, diversion or reversal of flood flow can be attributed to the coincidence between volumes of discharge from the various river systems with the dimensions of the flood plains. These flow patterns can be related to five distinct geomorphic tracts occupied by the modern river from its headwaters to the South Australian border.

Quantification of the natural hydraulic characteristics of the river channel and its flood plain is fundamental to the development of flood plain management strategies. Such strategies need to have regard for the significance of the substantial

flood pondage which exists within the flood plain of the river.

ACKNOWLEDGMENTS

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8

QUATERNARY STRATIGRAPHY OF THE DARLING RIVER NEAR TILPA, NEW SOUTH WALES

By J. M. BOWLER[1], EUGENE STOCKTON[2], AND MICHAEL J. WALKER[3]

ABSTRACT; The Moomba to Sydney gas pipeline trench exposed a sequence of late Quaternary landforms and sediments where it crossed the Darling River floodplain in western New South Wales. Stratigraphic sections and radiocarbon analyses along 20 km of the pipeline demonstrate a sequence of fluvial and aeolian phases that are comparable to events of similar age elsewhere in southern Australia.

Following alluviation about 30,000B.P., an episode of intensified dune building dated to between about 20,000 to 16,000 B.P. spanned the glacial maximum. Simultaneously with this phase the Darling River, draining summer rainfall areas to the north, entered a phase characterized by large meander wavelength channels subject to rapid lateral migration. In so doing it produced morphologic characteristics similar to those ancestral streams of glacial age in the Goulburn River in northern Victoria. This similarity in the behaviour of channels draining summer and winter rainfall catchments respectively demonstrates the widespread ability of glacial age hydrologic changes to produce similar morphologic and depositional expressions through widely differing climatic and physiographic regions.

The mechanism of anabranch formation in this region is related to the hydrologic changes that accompanied the end of the glacial age hydrologic environments and the initiation of suspended load Holocene channels. A similar mechanism probably explains the relationships between anabranches and modern channels downstream.

INTRODUCTION

The excavation in early 1975 of the gas pipeline trench linking Sydney, New South Wales, and Moomba in northern South Australia offered a rare opportunity to examine and document geological and soil structures over a large area of western New South Wales. In this way surface forms could be related to sub-surface sediments and structure. One such area of interest was that where the pipeline crossed the Darling River with its associated array of alluvial and aeolian landforms. In this paper we are concerned to describe the major units recognized and, by dating them, to provide new information on the chronology and environmental evolution of this region from which little detailed information was previously available.

The Area

Trending northwest from the Barrier highway, the pipeline intersected the Darling some 10 km downstream from Tilpa (Fig. 1). The area north and south of the Darling is one of very low relief broken only by dune ridges rising to about 12 m above the grey clay alluvial plain. Into this plain the channels of Acres Billabong, the Darling Anabranch and the Darling channel itself are cut.

The region is one of low rainfall and high evaporation. On the regional maps of the Commonwealth Bureau of Meteorology it lies near the 250 mm isohyet, with pan evaporation averaging more than 2000 mm per year. Thus the area lies on the arid margin of the semi-arid zone of south-eastern Australia.

Drainage

The Darling River, draining a large area of northwestern New South Wales and southern Queensland, receives most of its waters from summer monsoonal rains, although locally the Tilpa area receives approximately 40% of its rainfall from winter westerly circulation. Acres Billabong, now a largely inactive channel except

1. Department of Biogeography and Geomorphology, Australian National University, Canberra, A.C.T. 2601.
2. St. Patricks College, Manly, N.S.W. 2095.
3. Department of Anthropology, University of Sydney, N.S.W. 2000.

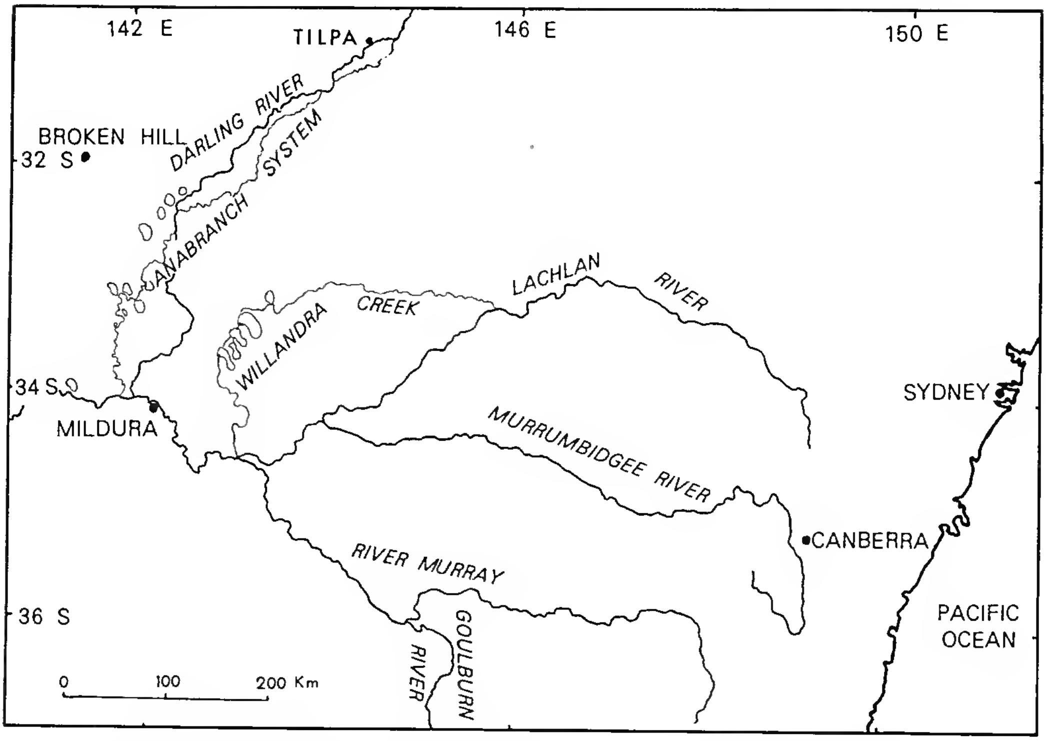

FIG. 1 — Rivers of southeastern Australia illustrating some localities discussed in text.

during high stage flows, represents an ancestral course of the Darling River. The present river channel breaks away from its ancestor near Tilpa, and at the pipeline crossing the ancient and modern channels are 14 km apart (Fig. 2). In rejoining 12 km downstream, Acres Billabong represents a typical anabranch.

Not only are these older and younger systems separated spatially, but perhaps more significantly they possess markedly different morphological characteristics. The Darling flows in a narrow meander belt with its channel retaining small meander wavelengths. By contrast the scroll bars and final channel form of the ancestral stream

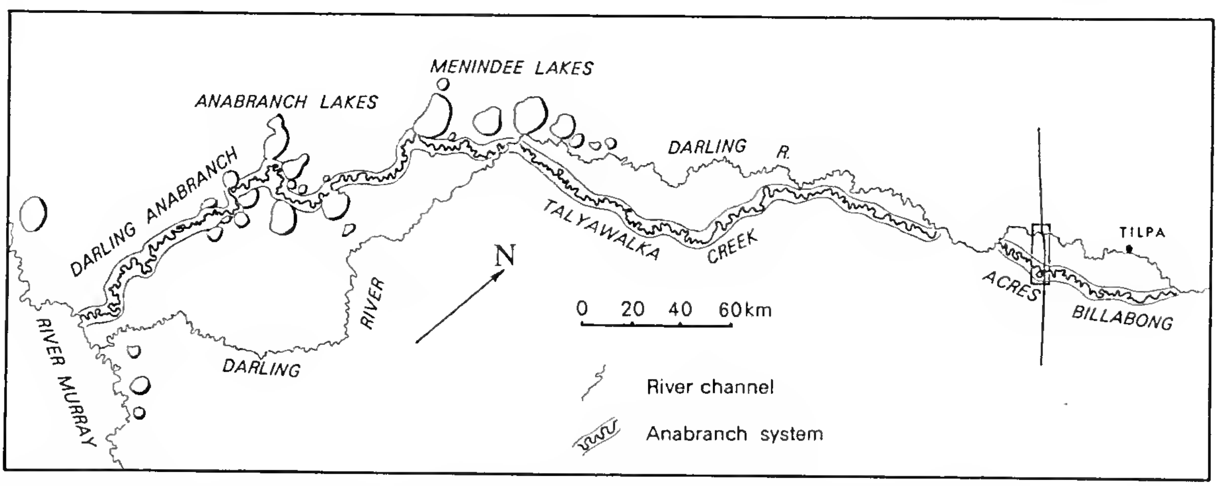

FIG. 2 — Diagram showing location of gas pipeline crossing Darling River and Acres Billabong. Downstream to the River Murray the modern channel has broken out of the anabranch systems which represent the ancestral course of the Darling dated in the pipeline section to between 20,000 and 11,000 B.P. Note association of lakes with the ancestral course. For inset see Fig. 3.

portray a highly sinuous course in a wide meander belt with characteristically large meander wavelengths and large radii of curvature.

The pipeline intersected three additional landform units. Throughout the region, rather irregular red quartz dunes maintain west to easterly trends reflecting the dominance of westerly winds. They often rise through extensive grey alluvial plains as though partly submerged by them. In the centre of the region is a small dry lake basin with multiple grey lunette ridges on its eastern side.

Aims, Organization and Methods

In examining data from this region Stockton and Walker mapped stratigraphic sections and collected radiocarbon dating material from the area north of the river where the trench intersected a red dune complex before dropping down onto a grey calcareous plain some 3 km from the channel. Within this region they identified soil-sedimentary units and plotted their lateral continuity. In the southern sector Stockton and Bowler mapped the region extending to Acres Billabong and collected ^{14}C samples from the ancestral pointbar sediments.

Time for detailed field examination was necessarily brief as only a couple of days lapsed between the opening of the trench and the laying of the pipe. In this report we provide a brief description of the aeolian and alluvial units represented, assess the value of the ^{14}C chronology obtained, and place some aspects of the hydrologic changes identified into a regional perspective. The landform map (Fig. 3) has been constructed from aerial photographs whilst detailed survey levels along the trench have been used to plot topographic and stratigraphic sections.

Radiocarbon analyses were carried out in the University of Sydney for Stockton and Walker (code SUA) and in the Australian National University for Bowler (code ANU).

IDENTIFICATION AND DESCRIPTION OF UNITS

The general stratigraphic cross-section (Fig. 4) displays the relationships between the main landform units and the sediments of which they are composed. In this sequence, ridges of red quartz sand protrude through a cover of grey clay. This latter alluvial component is dominantly younger than the core of quartz dunes. North of Acres Billabong the alluvium possesses secondary carbonate, in a soil profile with moderate to well developed prismatic jointing developed in clays with angular to blocky structure. This degree of pedality differentiates grey alluvial plain in the centre of Fig. 3 from those other alluvial bodies more closely associated with present drainage lines. Thus in the area extending 500 m north of Acres Billabong, grey sandy clays, often with sandy laminae dipping to the south, represent pointbar deposits of the ancestral stream; almost no profile differentiation was evident in such deposits. Clays lying to the north and south of the Darling River are considerably darker grey in colour than the older alluvial deposits, and they too lack horizon differentiation consistent with active overbank deposition in this flood-prone region.

North of the river, Stockton and Walker mapped an horizon of brownish red sandy clay loam to heavy clay that passes under both the main body of the sand dunes and under the Darling floodplain clays (Fig. 4). Charcoal from within this unit located 2 m below the floodplain and 0.8 km northwest of the Darling provided the oldest ^{14}C date available, 35,450 $\pm$ 1,600 B.P. From the configuration of this unit, which rises and forms the core underlying younger dunes, it is tentatively identified as an early aeolian deposit.

On the most northerly sector of the cross-section the basal red unit passes beneath grey silty clay representing older alluvium on which a grey calcareous paleosol has formed. Carbonate nodules from within this unit provide a ^{14}C age of 19,600 $\pm$ 460 B.P.

The dunes that form the most prominent ridges in the landscape have a deep red calcareous soil with nodular to earthy carbonate often forming zones up to 0.7 m thick. In its upper part the profile consists of non-calcareous red brown sand (2.5 YR 4/8) about 40 cm thick on crestal sites. From within the A-horizon sands carbon, perhaps representing burnt root remains, dated to 8,035 and 4,420 B.P. (Table 1).

In the section through the crest of the largest sand dune 2.5 km southeast of the Darling the strong red colours pass down through a Bca horizon to paler orange to yellow weakly calcareous quartz sands. This downward gradation in profile colouration indicates *in situ* rubefaction by pedogenic processes. This might further suggest that the origin of the sands lay in their derivation from washed channel sands rather than from the reworking of older aeolian materials. The red calcareous dune sands pass in a southerly direction under grey alluvial clay loam, which in turn grades laterally into lacustrine and lunette grey calcareous clayey sands.

The aeolian units are overlain in the centre of the region by a thin layer of well bedded quartz sands

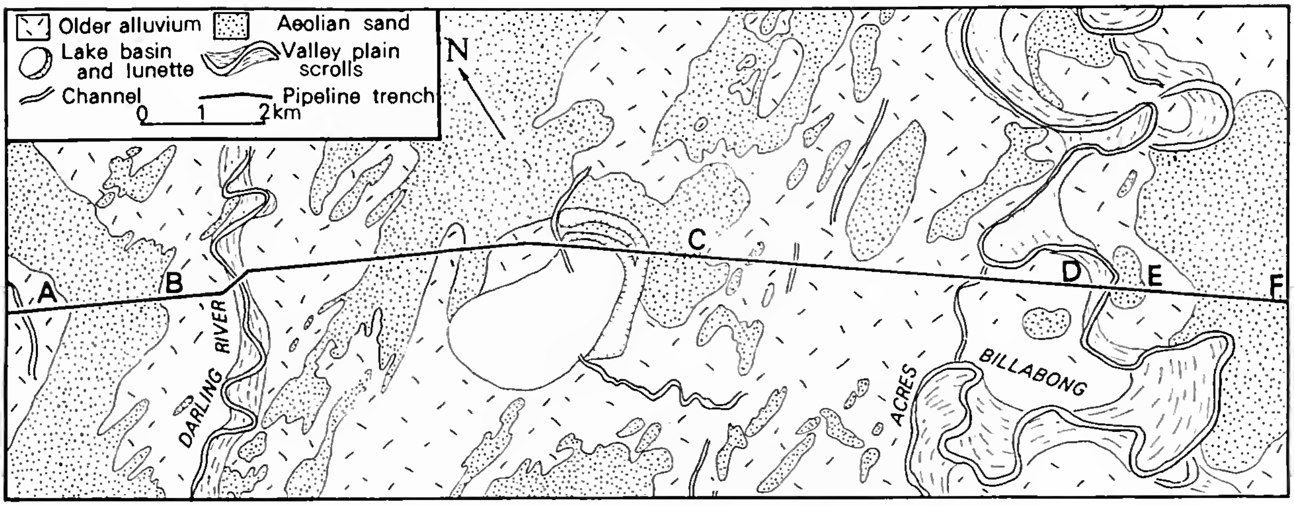

FIG. 3 — Map of landform units in the area intersected by pipeline trench across the Darling River near Tilpa.

usually less than 50 cm thick. The preservation of bedding indicates its recent origin as a windblown layer. Two charcoal dates collected by Stockton and Walker from 8 and 28 cm below this well developed bedded zone provide ages of 245 and 335 yr B.P. respectively (Table 1). These possibly represent roots intruding into the underlying layer. The age of the thin bedded unit is probably younger than the ^{14}C ages. It may relate to post-European disturbance by grazing.

Alluvial Chronology

Two main bodies of alluvium have been differentiated on Fig. 3: an older unit identified on the basis of its calcareous soil, and younger alluvium in which little or no pedogenic development testifies to its relatively recent origin. The younger alluvium is directly associated with both active and inactive channels.

For some 500 m the trench near Acres Billabong exposed sediment deposited by the southerly migration of that channel (Fig. 4). Here the alluvial strip associated with the ancestral stream is set into older grey calcareous alluvial clay. The contact exposed in the wall of the trench dipped to the south at 15°, representing the stratigraphic disconformity between these two alluvial units. Expression of the disconformity at the contact was a subtle one, depending more on the loss of primary bedding and the development of diagnostic soil characteristics in the older body. In the upper 50 cm a blanket cover of grey clays representing overbank deposits from the active phase of Acres Billabong masks the stratigraphic discontinuity which therefore has no

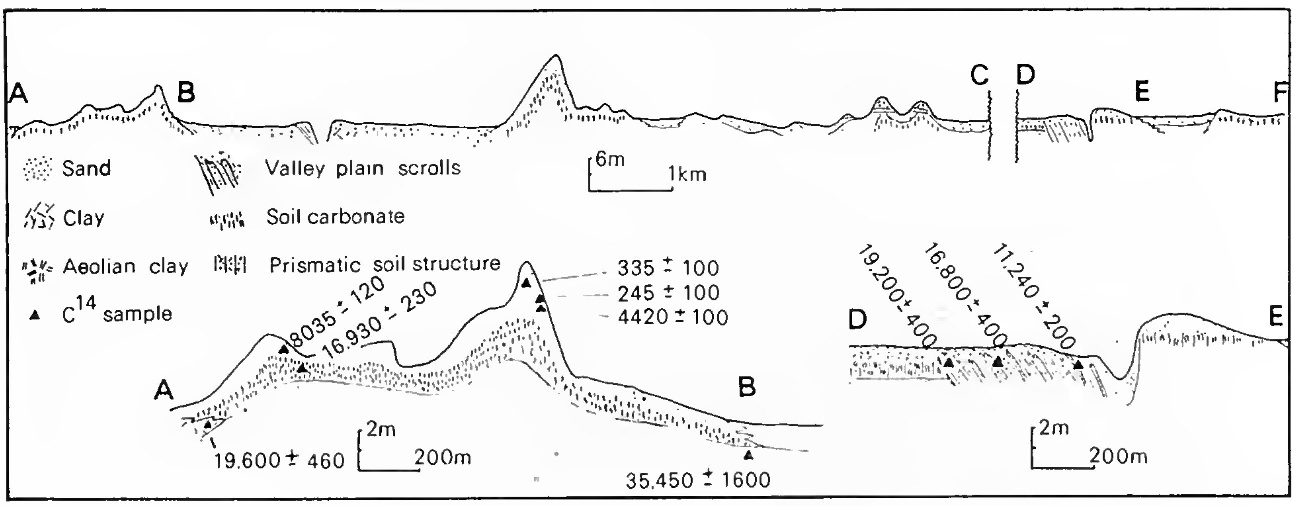

FIG. 4 — Stratigraphic cross sections through the area shown in Fig. 3.

TABLE 1
RADIOCARBON DATES FROM GAS PIPELINE TRENCH IN SECTIONS NORTH AND SOUTH OF DARLING RIVER

	Lab. No.	*^{14}C Age*	*Material Dated*
Sequence Northwest of Darling River Collected by E.S. & M.J.W.	SUA-448	245 ± 100	Charcoal from 20 cm below surface, 8 cm below base of uppermost layered aeolian sand located 1.15 km NW. of Darling River.
	SUA-447	335 ± 100	Charcoal from 40 cm in section 1.35 km NW. of Darling River.
	SUA-450	4,420 ± 100	Charcoal from 100 cm below surface in base of zone interpreted as A-horizon of red calcareous soil on dune 1.15 km NW. of river.
	SUA-440	8,035 ± 120	Charcoal from position stratigraphically equivalent to SUA-450 in section 1.55 NW. of river.
	SUA-446	16,930 ± 230	Top of calcrete crust in red calcareous paleosol on dune (Fig. 4A).
	SUA-438	19,600 ± 460	Calcrete developed in grey alluvium at approx. 1.5 m depth, 1.5 km NW. of river.
	SUA-435	35,450 ± 1,600	Charcoal from 2 m below floodplain 0.8 km NW. of river from within basal reddish brown sandy clay of probable aeolian origin.
Acres Billabong Sequence Collected by J.M.B. & E.S.	ANU-1982	11,240 ± 200	Charcoal pellets from burnt surface dipping 14° to SE. within pointbar clayey silts 100 m NW. of Acres Billabong.
	ANU-1993	16,800 ± 400	Charcoal from layer f reddish oxidized clayey silts indicating *in situ* burning on bedding plane dipping 15° SE., 390 m W. of Acres Billabong.
	ANU-1984	19,200 ± 400	Charcoal in layered zone 2 cm thick dipping to SE. in grey silty pointbar deposits 530 m NW. of Acres Billabong and 6 m from discomformable contact with older alluvium.

clear surface expression. However at depth in the lower part of the trench the disconformity was clearly apparent.

From 6 m south of the disconformity and 540 m north of the channel, charcoal from a southerly dipping band within sediments of Acres Billabong phase provided a ^{14}C date of 19,200 ± 400 B.P. Since the disconformity here marks the first stage in the development of Acres channel, this event must be placed close to 20,000 B.P.

Charcoal samples from similarly dipping bands located 390 m and 100 m north of the channel provide ^{14}C ages of 16,800 ± 400 and 11,240 ± 120 respectively, as in Table 1.

Expressed in terms of rates of pointbar accretion (Fig. 5) the dates indicate an almost linear rate of change. The position of the sample dated to 11,200 B.P. from within the segment slightly inset below the main level of the pointbar phase (Fig. 4) suggests that a change in the depositional nature of Acres channel regime occurred somewhat before that time.

DISCUSSION

AEOLIAN STRATIGRAPHY

The oldest date in the sequence (SUA-435) provides a maximum age for the development of the older alluvium. Moreover the charcoal was within what we believe to be ancient aeolian materials; this early dune building phase is older than 35,000 B.P.

Dates from soil carbonate horizons provide only approximate ages for deposition and soil formation in these environments. Whilst Bowler and Polach (1971) regard them as usually indicating minimum ages Williams and Polach (1971) have interpreted them in arid regions as indicating ages close to initial soil formation. However, bearing this uncertainty in mind, the samples SUA-446 and SUA-438 bracket the deposition of the main aeolian unit, provided contamination of the lower sample (438) through the aeolian sand can be excluded. Since we can not eliminate this possibility, the evidence may be interpreted to

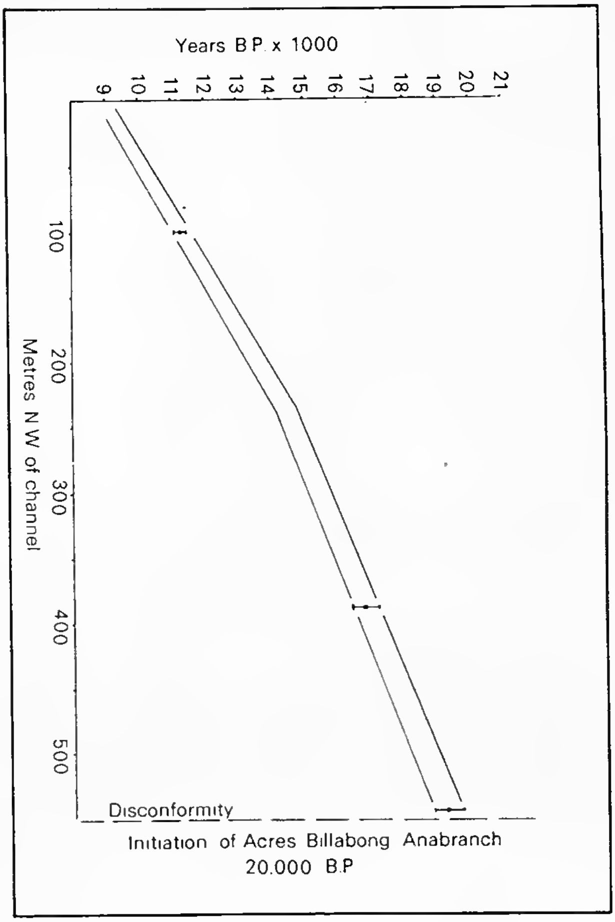

FIG. 5 — Curve envelope showing the rate of lateral migration of Acres Channel since its inception about 20,000 B.P. until its abandonment about 10,000 B.P.

indicate alluviation between 36,000 until sometime before about 20,000 B.P. Pedogenesis followed, perhaps synchronously with aeolian activity.

In considering the age of the next aeolian event, account must be taken of the limitations of carbonate dates. The process of attaining equilibrium between parent carbonate and soil atmosphere during the formation of pedogenic nodules may not have gone to completion. The true age of the soil calcrete may even be somewhat younger than the ^{14}C ages suggest. However, for the upper sample (SUA-446) at least, in view of the age of the underlying unit, it could not be much older than 17,000 B.P. Conversely, the age of pedogenesis indicated by the lower carbonate date (SUA-438), whilst it may be somewhat older than 19,600, certainly could not be significantly younger. Therefore, the age of aeolian deposition is bracketed between about 20,000 until soon after 16,000 B.P.

The two dates from aeolian units higher in the sequence (SUA-449 & SUA-450) are open to alternative interpretations. Coming from within the A-horizon of the red calcareous soil, they probably represent burnt tree remains that grew in that soil. As such they indicate relative stability until at least 4,000 B.P.

The main aeolian unit is that which constitutes the body of the dunes. Its age is in good agreement with the last phase of major aeolian activity postulated from evidence further south, as having occurred between 25,000 and 16,000 B.P. with the peak development about 17,000 B.P. (Bowler 1970). Thus it appears that events of maximum glacial age were expressed here also by intensified aeolian activity simultaneously with that which seems to have affected the entire region of southern Australia.

Some 130 km to the south of Tilpa, a younger episode of dune building has been recorded by Wasson (1976) in the Belarabon area. However this event, which lies between 3,000 and 600 B.P., does not appear to have any distinct expression in the region studied. This may be due more to a preceding phase of alluvial deposition in the Belarabon Ranges as Wasson suggested, and the relative absence of such reactivation on the Darling floodplain.

ALLUVIAL STRATIGRAPHY

1. *Chronologic sequence.* The ^{14}C chronology suggests the following sequence of events in the alluvial history of the region. Between 36,000 and about 20,000 B.P. active floodplain deposition was taking place, particularly in the area north of the Darling. Traces of an ancient channel lying just on the northern edge but mainly outside the mapped area in Fig. 3 probably represent the course of the Darling at that time.

About 20,000 B.P. avulsion and channel diversion occurred with the development of the first phase of Acres Billabong. Maintaining its characteristically large meander scroll pattern, it continued to widen its belt in a sinuous course for some 8-9,000 years. Soon after 11,000 B.P., a second avulsion took place with the development of the present course of the Darling north of Acres channel, which then became progressively abandoned.

2. *Significance of Acres Billabong.* The contrast between the morphology of the modern channel and that of Acres Billabong points towards major changes in the hydrologic regime. Elsewhere in southeastern Australia a similar contrasting rela-

TABLE 2
MORPHOLOGIC PARAMETERS OF DARLING RIVER AND ACRES BILLABONG AS REPRESENTED BY TRACE OF CHANNELS AND SCROLLS ON FIG. 3.
Amplitude, curvature and wavelength measurements in metres with variation to one standard deviation. Measurements of the Goulburn River and its glacial age ancestral course from Bowler (1978).

CHANNEL SYSTEM	DARLING	ACRES	GOULBURN	KOTUPNA
Sinuosity	1.45	2.35	1.58	1.23-2.02
Meander amplitude (m)	575 ± 150	1,620 ± 250	730	1,340
Radius of curvature of scrolls (m)	297 ± 94	670 ± 210	NA	NA
Meander wavelength (m)	1,050 ± 164	2,190 ± 260	550	3,000

tionship exists between modern and ancestral channels. On the Goulburn River in northern Victoria, channels of an ancestral phase (the *Kotupna* of Bowler 1978) possessed meander features many times larger than those of the modern Goulburn. But most significantly the ages established here for the active migration phase of Acres Billabong, 20,000 to 11,000 B.P., are similar to the ages of channels with comparable morphology in the Goulburn valley. There the ancestral features were active from at least 25,000 until about 13,000 B.P.

When compared in detail (Table 2), the relationships between Goulburn-Darling palaeochannels and their modern successors exhibit a number of striking similarities. A ratio of ancient to modern meander belt widths in the Goulburn of 2:1 is similar to that of Acres Billabong compared with the Darling meander belt. In both areas, meander belt widths were developed by lateral channel migration. The pipeline trench intersected Acres Billabong near a nodal point of minimum meander enlargement. However scroll bars on large meanders east and west of the section (Fig. 3) indicate channel migration of 1.5 to 1.8 km. Over the period 20,000 to 11,000 B.P., this is equivalent to a migration rate of 17 to 20 cm per year, a figure that corresponds almost exactly with the channel migration rate established for the Kotupna ancestral phase on the Goulburn (Bowler 1978).

In one feature palaeochannels of the Darling and Goulburn are different from each other. In Acres Billabong, deposition and scroll bar development indicate bank erosion on the outside edge of meanders producing a progressive lateral enlargement, increasing sinuosity but producing little down-valley migration. By comparison, channels of the Kotupna phase migrated down-valley leaving a train of meander scrolls in a broad belt of alluvium. In Acres Billabong there was a progressive decrease in the channel bed gradient whilst in the Kotupna system the broad meander belt, once established, migrated downstream preserving constant gradient of the channel bed. The mechanisms responsible for this different behaviour are not understood.

The similarity in form and the correspondence in age of these large meandering palaeochannels from catchments which experienced entirely different climatic regimes throughout the period of the maximum global refrigeration from at least 20,000 to 13,000 B.P. sheds new light on our understanding of the underlying causes. In the Goulburn, draining the cold highlands of southeastern Australia with dominant winter rainfall, the explanation offered by Bowler (1978) for the hydrologic changes involved a combination of increased discharges in ancient channels associated with bed load yield higher than in the modern regime. The higher quantity of sands in glacial age channels could be explained by two factors. Firstly, upland slopes, denuded of woodland vegetation by periglacial activity, would have contributed large quantities of detritus into headwater streams. Secondly, the rapid migration indicated by radiocarbon ages in Kotupna palaeochannels involves bank erosion, sorting, and redeposition of sediment loads much in excess of those of the modern stream. These two processes would have combined to produce much more sand than in the suspended load channels of today.

In the Darling catchment, the influence of periglacial activity must be ruled out. The factors common to both Goulburn and Darling streams that contributed to the similarity in form and behaviour of palaeochannels may be summarized as follows:

1. Channel-forming discharges of glacial age were probably considerably in excess of those in the past 10,000 years. In both Queensland and the Victorian highlands reduced glacial age tem-

peratures would have contributed to a drastic reduction in evapo-transpiration with a consequent increase in availability of surface water. In catchments affected by loss of woodland vegetation this effect would be amplified by faster runoff. Whilst riparian woodlands were absent from the Murray-Goulburn systems at this time (Bowler 1978) the vegetation association along the Darling channels is not known.

2. In addition to increased discharge, the evidence suggests that palaeochannels of both systems contained coarser bedloads than their modern equivalents. In Acres Billabong, the persistence of sandy lenses across scroll bar sections (Fig. 4) supports this view. As established by Schumm (1960) this factor will contribute significantly towards explaining larger channel morphology. The synchroneity reaffirmed between the ages of the large meander phase and active dune building about 17,000 B.P. means that much sand would have been blown into the channel of the Acres system. Such sand, possibly derived from earlier phases of alluviation, would have helped change the bedload regime, at least in the Darling area where dunes were active at the time. However, on the Goulburn the evidence suggests that sands were blowing out of, but not into, the palaeochannels.

3. The rapid meander migration rates established in both systems point to bank failure occurring at rates much higher than today. In addition to the possible absence of channel margin woodland, two additional factors may have been operating in both regions. Firstly, bank failure is enhanced by rapid draw-down of the level of water in the channel relative to the level of saturated pore water in the banks. Low bank cohesion combined with high pore water pressure results in increased bank failure. The faster the flood wave falls, the more bank failure will occur. Thus the more peaked the flood wave, the more rapid channel and meander migration will result.

Peaked flood waves will be favoured by conditions of enhanced seasonality. Such claims have been made for glacial age conditions in this part of southeastern Australia (Bowler *et al.* 1976). But to explain features common to both the Darling and Goulburn regions this would require greatly increased seasonal contrast in the summer rainfall on one hand and in winter precipitation on the other. However, since the high stage Goulburn discharge would be controlled by late spring-summer thaw of highland snowfields, the result would be increased summer flow from the winter catchments which would then coincide with high stage summer flow from the monsoon region. In this respect the seasonal high stage flows from both streams would have been much more closely timed than they are today.

The second factor that may have played a major role in enhanced bank failure concerns the regional and local watertable. The presence of regionally high watertables will have an effect similar to that described for rapid river draw-down following the passage of a flood wave. A fall in river level in an area of high watertables will result in a sustained level of pore pressure inducing more rapid bank failure than if watertables are low as in the present regime. The effect of increased return flow through the banks would be much the same as that described for the passage of a peaked flood wave.

The study of lake basins throughout a large area of northern Victoria and southwestern New South Wales has demonstrated the widespread and simultaneous construction of saline clay-rich lunettes in the interval between 20,000 and 15,000 B.P. (Bowler 1976). Their construction requires the presence of saline watertables at or near the surface over extensive regions. Under such conditions, low stage flows in rivers would be accompanied by high pressures on the banks inducing active bank failure. The presence of a small lake in the central part of the pipeline section south of the Darling with an ancient calcareous lunette whose age is apparently similar to those dated elsewhere, provides strong supporting evidence that high watertables here, as in the Goulburn Valley, contributed to rapid bank failure and accelerated meander migration.

Relevance to Darling Anabranches

The features described here bear on our understanding of the regional geomorphology of the Darling River. One of the anomalous features of Australian fluvial geomorphology is the common occurrence of complex anabranching channels on the inland plains. Indeed the best known example, the Anabranch of the Darling, occurs only 250 km downstream from the Tilpa pipeline section (Fig. 2). The ages and causes of anabranch development hitherto unexplained may be reviewed in the light of the Acres Billabong evidence.

In the Darling system downstream from Tilpa palaeochannels occur that possess morphologic characteristics identical with those described here from Acres Billabong (Fig. 2). Thus downstream from Acres Billabong, Talyawalka Creek follows one such diversion south of the Darling; in its meander belt ancient scroll bars preserve patterns identical with those of Acres Billabong. These cross the Darling near Menindee and continue west

towards Lake Tandou in the course now occupied by Redbank Channel. Downstream this system is known as the Darling Anabranch. Thus not only do the palaeochannels show similar morphology to that of Acres Billabong but its history of avulsion and anabranch formation under an ancient regime may be common to all such examples in this locality. It is significant that the modern Darling tends to avoid the course of the ancestral channels in the tract extending from Tilpa downstream to the River Murray junction.

With the evolution of the large meander regime characterized by Acres Billabong, the increased sinuosity and progressive reduction in channel gradient eventually resulted in a major loss of efficiency. Under conditions of diminishing discharge such as may have existed in the transition from glacial age to Holocene regimes (from about 14,000 to 10,000 B.P.) these systems were sufficient to carry the water load. About 10,000 B.P. the evidence from southwestern Victoria (Dodson 1974, Bowler *et al.* 1976) and northwestern Queensland (Kershaw 1975) indicates the onset of a period wetter than today. In the south at least, this was accompanied by a return of trees to channel margins. Thus it represents the initiation of hydrologic and vegetational environments rather similar to those of today. Under these conditions the ancient channels proved too inefficient to carry waters of the changed regime. It was such an inbalance between the requirements of the new hydrologic phase and the highly inefficient and sinuous system of the ancient form that helped bring about avulsion with the development of straighter channels possessing steeper gradients which more effectively transport the waters of the present regime.

The evidence presented here establishes the widespread influence of the glacial age hydrologic environments on catchments draining the summer rainfall area, a feature previously known only for the winter catchments. Moreover the evolution of glacial age channels and their progressive loss of efficiency has been a real factor in the formation of anabranches with younger more efficient channels breaking out to follow newer courses. Recently Woodyer, Taylor and Crook (in press) have described a model to explain anabranch development by progressive plugging of suspended load channels by deposition of clay. This mechanism involves no hydrologic change and in the area from which their evidence was drawn, the Namoi-Barwon rivers, it may be the single responsible mechanism. However, in the lower reaches of the Darling, anabranching was associated with hydrologic changes that accompanied the transition from late glacial to Holocene regimes.

CONCLUSIONS

The sections exposed in the pipeline trench demonstrate a sequence of landforms and sediments, each phase of which is related to climatically controlled events in a changing hydrologic environment.

About 30,000 B.P. active alluviation was occurring in the region north of the present Darling channel. This phase was followed about 20,000 B.P. by the onset of aeolian activity which produced new, and remoulded older, sand dunes throughout the region. Radiocarbon dates place the timing of this event between about 20,000 and 16,000 B.P., in excellent agreement with the age of maximum aeolian activity established elsewhere in southern Australia.

Simultaneously with the onset of dune building the Darling River, carrying discharge through the region from well-watered areas of southwestern Queensland, cut a new channel which ultimately evolved into the present course of Acres Billabong, a typical anabranch of the lower Darling system. The hydrologic regime of this phase produced rapid lateral migration of the channel, the size and shape of which was drastically different from that of the modern Darling. The morphologic relationships between the glacial age ancestral and modern channel in this region bear a striking similarity to those that existed between the modern and ancient Goulburn River in the winter rainfall regime further south. The similarity between ancestral rivers draining both summer and winter catchments is believed to be due to increased bedload regimes associated with increased peak discharges in systems flowing through areas of regionally high watertable. Stages of low flow with seasonal reversal of piezometric gradients resulting in a long period of groundwater return through the banks would help produce the high rates of bank failure necessary to explain channel migration rates of 20 cm/year for a duration of more than 7,000 years. Increased rate of bank failure and lateral enlargement of meanders may have been enhanced by flood-wave conditions more peaked than those of today, a condition favoured by stronger seasonality of glacial age climates.

The Acres system probably entered its waning phase about 13,000 B.P. having already achieved a highly sinuous, low gradient course. Soon after 11,000 B.P. avulsion occurred, the new channel leading to the development of the present Darling. This event may have been due to an increase in

stream flow about that time, the Acres channel having become so inefficient that it proved incapable of accommodating the increased discharge. The similarity of both the ancestral anabranches and the modern channel downstream with those relationships established near Tilpa suggest that the causes of anabranching in the lower Darling are identical with those proposed from the pipeline section.

Finally, the synchroneity in age and similarity in form between aeolian and fluviatile landscapes of the Darling region, when compared with related forms in the winter rainfall region further south, demonstrate the ability of glacial age processes to produce similar features throughout widely differing climatic and physiographic regions, an ability that is even more remarkable in the light of the differences that exist between those regions today.

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THE GEOMORPHOLOGY OF THE UPPER DARLING RIVER SYSTEM WITH SPECIAL REFERENCE TO THE PRESENT FLUVIAL SYSTEM

By S. J. RILEY[1] AND GRAHAM TAYLOR[2]

ABSTRACT: Five distinct regions are evident in the Upper Darling River System, namely, the eastern hill lands, the western alluvial plain, the Barwon dominated region, the Pilliga sand plain and the Lightning Ridge region. Two thirds of the total area of 300,000 km² is dominated by alluvial deposits and direct river action.

Stream morphology and regime change dramatically in the transition from the hill lands to the plains. Distributary patterns dominate the plains. Sediment load of streams on the plain is wash load. The plains are aggrading at an average rate of 2×10^{-2} mm/yr and, in the eastern areas, have a definite alluvial fan morphology.

Stream gradients across the plains are of the order of 5×10^{-5}. Channels are sinuous, narrow and have low width-depth ratios. Bench development is active.

Paleo-channel sedimentology and morphology suggest fluvial regimes different from those of today. However, the difference in regimes need not be related to climatic or tectonic change. Changes in fluvial regimes can be associated with the progressive degradational-aggradational development of the fluvial system under constant external conditions.

INTRODUCTION

Although the upper Darling River basin has been settled since the 1850s (Jeans 1973), little in the way of scientific study of the streams has been done in the area as a whole or on the river system which has been and is increasingly important to the area. With the exception of stream flow and climatic records, little is known of the area in terms of present-day geomorphic processes or of the genesis of the landscape.

This paper discusses recent advances in the study of the area, particularly with respect to the morphology and sedimentation of the Darling River in the area east of Brewarrina.

The authors would like to point out that, because there is so little information in the area, there is much scope for speculative thinking. As a consequence they do not entirely agree, on all the points presented herein. However, they have endeavoured to present the many facets of each argument as fairly as they can.

THE CATCHMENT

The Darling-Barwon River upstream of Brewarrina has a catchment area of 300,000 km² (Fig. 1). With the exception of several small south-flowing streams between Walgett and Brewarrina the major tributaries originate in the eastern highlands.

The eastern region of the catchment, approximately one-third of the upper Darling system, is distinguished by low to high-relief (up to 1,000 m) hill land topography. The remainder of the catchment is relatively flat (relief less than 300 m). The eastern third is composed of Palaeozoic sandstones, shales, intermediate to acid volcanics, granites, and Cainozoic basalts which crop out in many places or are covered with a relatively thin veneer of colluvial/alluvial material. The remaining two-thirds of the catchment are, on the whole, covered with Quaternary and older alluvium. There is some aeolin surficial cover in the northwest of the catchment.

The area of fluvial deposition extends westwards from the western margin of the eastern highlands. Surface gradients in the alluvial plains range from 10^{-4} near Moree to 10^{-5} near Brewarrina.

The catchment can be subdivided into five major physiographic regions:

1. The eastern hill lands.

1. School of Earth Sciences, Macquarie University, North Ryde, N.S.W. 2113.
2. School of Applied Science, Canberra College of Advanced Education, Canberra, A.C.T. 2616.

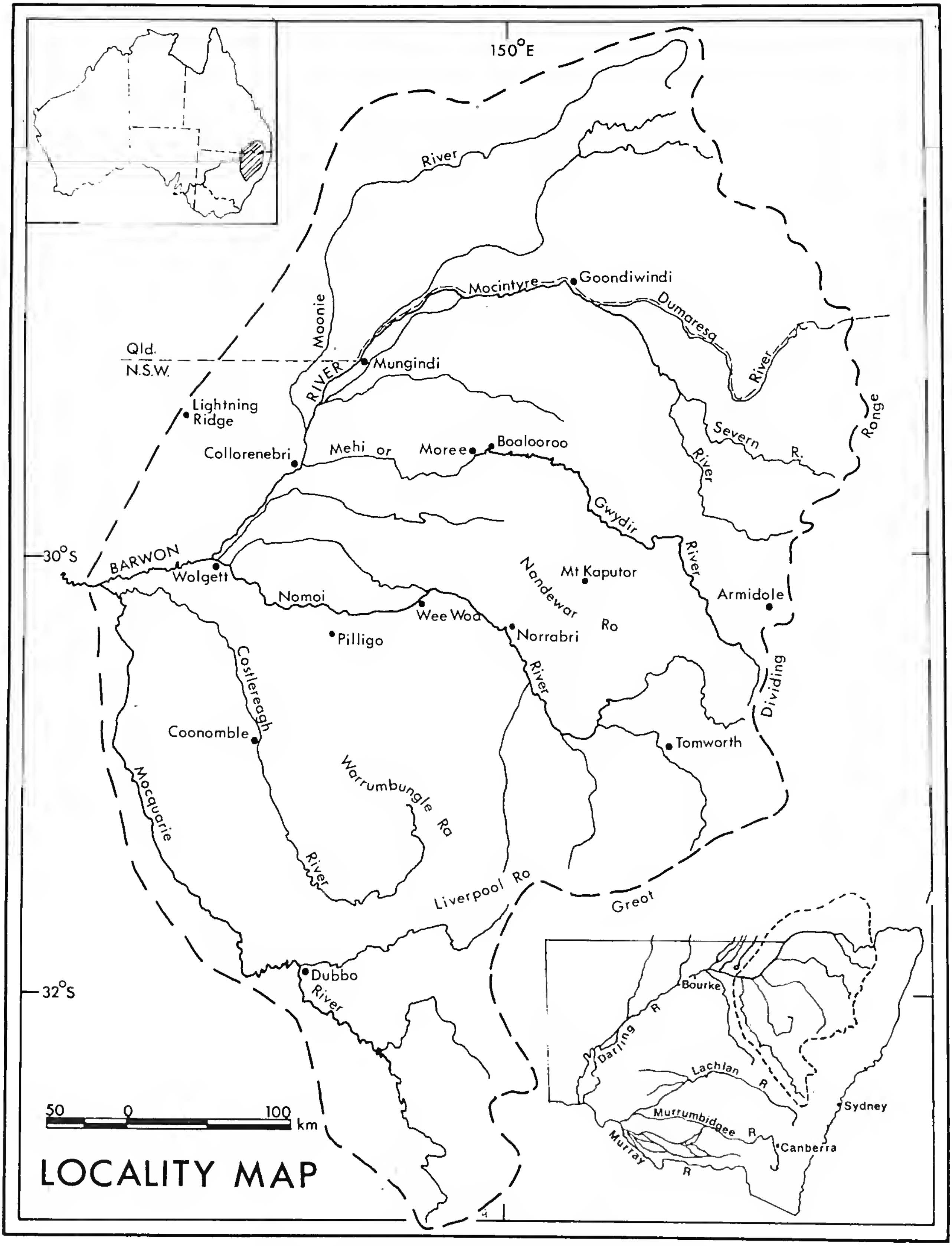


FIG. 1 — A locality map for the Upper Darling Basin.

2. The distributary-dominated, western alluvial plain.
3. The Barwon and Darling river-dominated region.
4. The Pilliga sandplain region.
5. The northwestern Lightning Ridge region of low hill lands.

Each of these will be looked at in greater detail in subsequent discussions.

Details on the climate and hydrology of the Upper Darling Basin are discussed in various Water Resources Commission publications for major streams in the area. It is important to note that towards the west there is a marked decline in runoff per unit area and precipitation and a rapid increase in mean maximum temperature and annual evaporation. The implications of these regional climatic and hydrologic gradients will become evident in the following discussion.

HYDROLOGY

The average discharge for several gauging stations are presented in Table 1. Direct comparisons between the stations are somewhat difficult because they have been operating for different periods and, more importantly, they have not been accurately rated in the upper half (in some cases upper two thirds) of their estimated discharge range. Logistic problems during floods and the interference of numerous distributaries which become active during high stages make it difficult for accurate discharge results to be obtained. Nevertheless, Taylor estimates that approximately 70% of the stream flow from the eastern highland streams actually passes into the Darling. The remainder is lost to groundwater seepage and evapotranspiration across the alluvial plains region (region 2).

Water velocities tend to be remarkably constant along the rivers for flows of similar frequency (Riley 1973). However, there appears to be a downstream decrease in velocity for discharge less than bankfull floods.

Flood hydrographs show considerable attenuation downstream. Consequently, downstream stations tend to receive smaller peak discharges than upstream stations provided no tributaries join between the stations. However, the downstream stations are usually in flood conditions much longer than the upstream stations, with resultant differences in the degree to which sediments (clays) can be dispersed and mobilized and the periods during which floodplain and channel are subject to high shear stresses.

SEDIMENT LOAD

The nature of the sediment load varies downstream and between the tributary streams. The majority of the load comes from the eastern tributaries and directly from the eastern hill lands of the upper third of the catchment.

Distinct differences in sediment load are suggested by the nature of the bed and bank material of the streams. In the east, sands and gravels dominate stream beds, with clearly defined point bar deposits and in-channel bars composed of these textures. Western streams have little sand on their beds, and that which does exist appears to be a thin layer. Unfortunately, no clear distinction can be made between the streams in terms of modes of sediment transport because it is not clear at present whether the clay is transported as flocculated particles of sand-size or as discrete particles less than 2 μm. Riley has noted convex bank deposits that resemble point bars but that are composed of silts and clays. The only detailed sampling of sediment load in the area is that which has been

TABLE 1
DISCHARGE AND GAUGING CHARACTERISTICS OF SELECTED STREAMS IN THE UPPER DARLING RIVER SYSTEM[1]

River Station	*Period record (yrs)*	*Average discharge (M^3/sec)*	*Estimated maximum discharge (M^3/sec)*	*Maximum gauged discharge (m^3/sec)*
Walgett	86	68	1712	642
Brewarrina	43	60	1472	743
Menindie	92	102	2830	689
Bourke	29	121	4075	2550
Wilcannia	86	101	2745	560

[1]*From Water Resources Commission of N.S.W.*

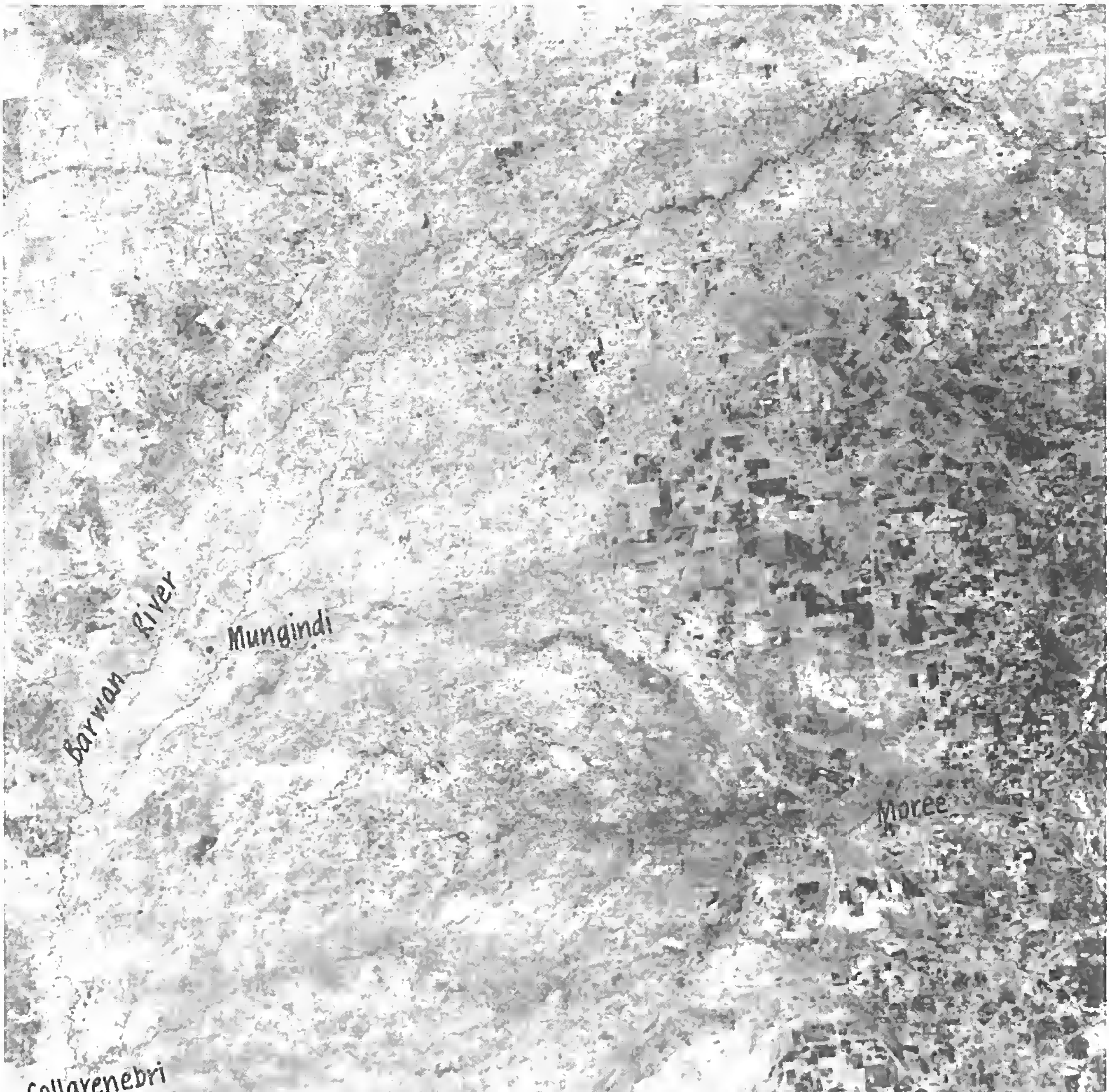


PLATE 9A
LANDSAT photo, Band 5, of 27th August, 1972 of the Gwydir distributary system.

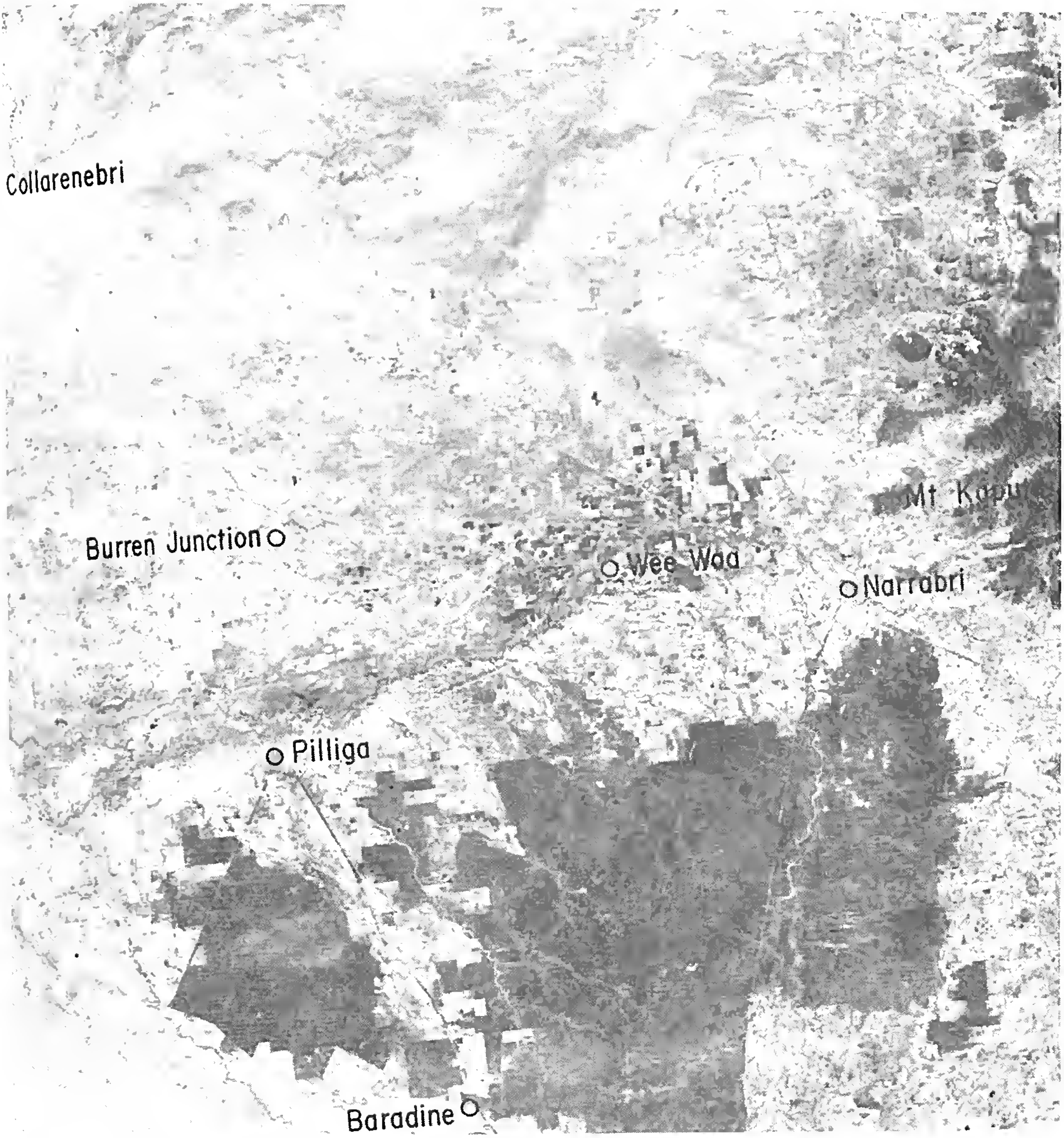


PLATE 9B

LANDSAT photo, Band 5, of 18th January, 1973, of the Namoi distributary system, Pilliga Sand Plain, and interaction zone between Namoi and Gwydir distributary systems.

conducted by Woodyer and Taylor (see Woodyer *et al.* 1977).

The relation between sediment concentration peaks and discharge are complex. At Walgett, of an annual sediment discharge of 500,000 tonnes 95% is washload, of which 80% is montmorillonite clay. The washload sediment concentration peak is preceded by the flood wave in the case of within-bank floods, but precedes the flood peak in the case of overbank floods (Woodyer 1978).

As stage increases the amount of bed-load and suspended-load appears to increase. However, the total suspended-load is small, as no sand has been sampled in suspension and it must be rapidly deposited out along the channel.

Taylor (1976) estimates from the Langbein and Schumm (1958) curves and subsequent modifications that 8×10^6 tonnes per annum of sediment are transported in the Upper Darling system, but that only 5×10^5 tonnes per annum pass through the Barwon at Walgett. Thus it appears that 7.5×10^6 tonnes of sediment per annum are deposited over the western alluvial plain or trapped in the low-order tributary valleys of the eastern hill lands. However it must be remembered that the estimated value is subject to error. We estimate that the dissolved-load is of the same order, and probably greater than the particulate load.

REGIONAL DEPOSITION

There is evidence that the bed material load transported from the eastern hill lands is largely deposited at the eastern edge of the western plain. The deposits take the form of large, low-angle alluvial fans and exhibit many of the morphological properties of fans (Wasson 1974 and pers. comm.). The evidence for deposition is:

1. The distinct change in morphology of some of the westward-flowing streams as they traverse the plains. Many which have wide sand beds or clearly-defined sand ripple and line features in the east do not have these features in the west.
2. There is a general westward decline in the proportion of sand in stream beds and in the median grain-size of bed sediments (Riley 1977).
3. Numerous distributing channels pass through swamps which would trap all but the finest of sediment.
4. LANDSAT imagery suggests that deposition in the form of alluvial fans is occurring (Pl. 9).
5. There is ample evidence from local farmers around Moree that the terminus of the Gwydir has been an area of considerable aggradation (reports of fences and stock yards being buried in periods of 20 to 40 years).

There is, however, some evidence to suggest that the aggradation is not great over the long term, and that it is very localized. This evidence is:

1. The thickness of the western plain alluvial deposits suggest rates of aggradation of the order of 2×10^{-2} mm/yr for the whole of the Namoi and Gwydir fans but these are probably at present of an order of magnitude less.
2. There is no conclusive evidence that bed loads of coarse sand and gravels are being transported along the Gwydir and Namoi Rivers at high rates. Riley (1973) notes that the median grain-size for the terminus of the Gwydir is in the silt and fine sand fraction and not the gravel that is exposed farther upstream of Boolooroo.

For the Namoi and Gwydir the real situation is probably one of localized deposition at the point where distributary offtakes are most prevalent and of uniform transport rates and low sedimentation rates across the alluvial plain. For the Macquarie and Castlereagh Rivers the situation is somewhat different, as they appear to drain areas which deliver large amounts of sediment to the streams. The wide sandy bed of the Castlereagh contrasts markedly with the beds of the Namoi, Gwydir, and even Maquarie Rivers.

STREAM MORPHOLOGY

There are significant morphological differences between the distributaries and parent streams of the western plains (Riley 1973). These differences are a result of differences in frequency of flow and sediment loads transported by the respective channel systems.

Distributaries are by no means stationary systems. At any one point in time some streams are expanding at the expense of others in the system. This temporal variation is illustrated in the Gwydir system by the Mehi, which seems to be in the process of capturing the lower end of the Gwydir River channel. A consequence of the transient nature of the channel system is that many features observed in the system may be a result of temporal change rather than spatial change. Unfortunately, because the rates of change for the area are not known, it is impossible at present to separate spatial and temporal effects. Thus, to label as relict any stream in the distributary system which transports water and sediment is to relegate it to a position that may not be warranted in the dynamics of the system.

Taylor (1976) thought that, for anabranching distributaries near Walgett, the morphology of the streams suggest channels that transported much greater suspended loads and discharge than does

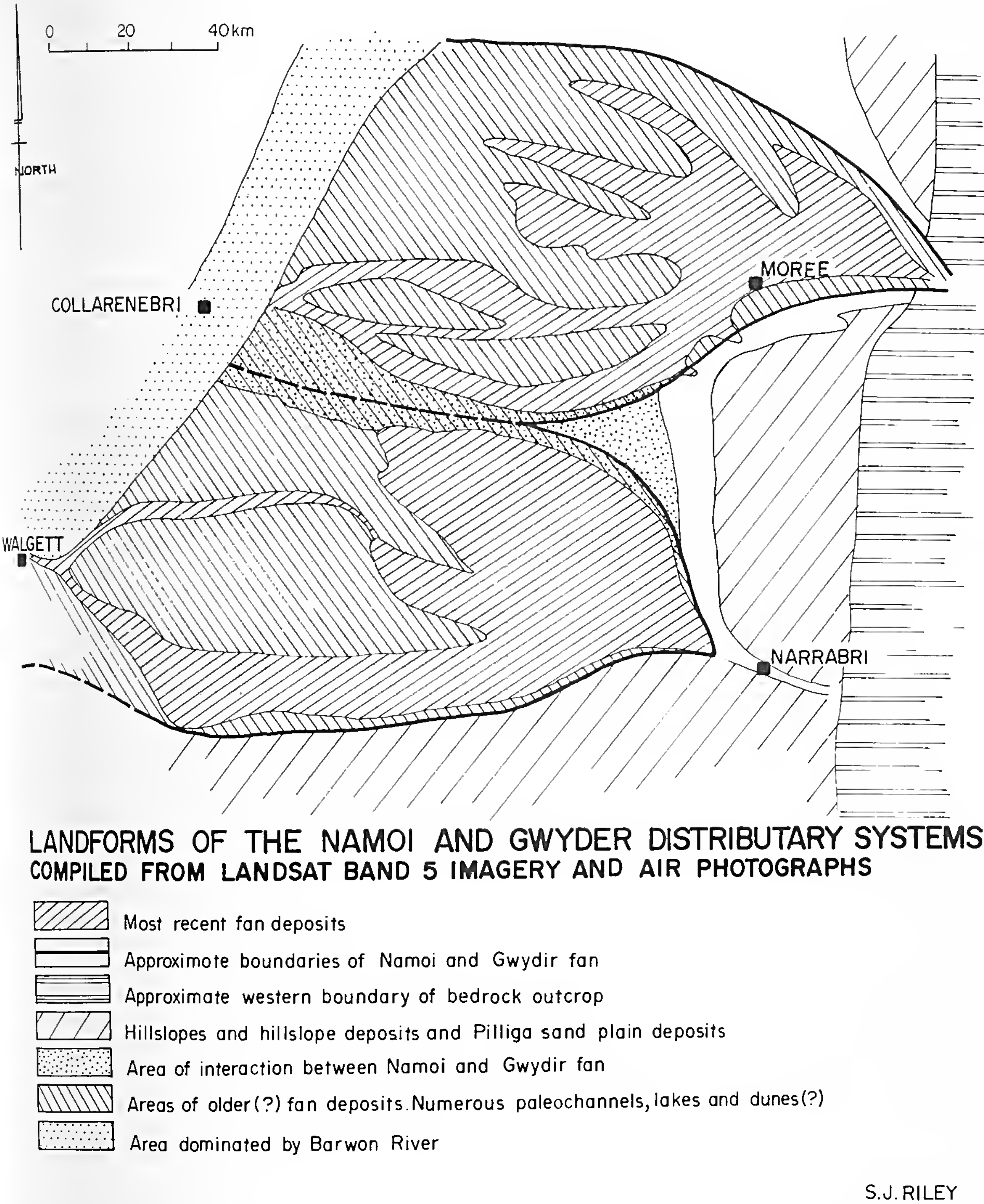


FIG. 2 — A geomorphic map of the Namoi-Gwydir distributary system.

the present Barwon-Darling system. That is, there is a clearly defined palaeochannel system suggesting discharge regimes different from those of today.

GENERAL REGIONAL GEOMORPHOLOGY

Eastern Hill Lands Region

There is a distinct north-south oriented demarcation line east of Narrabri and Moree that separates the eastern hill lands from the western distributary areas. This line is marked by a belt of folding and faulting and degraded volcanic landforms, and is best defined in the vicinity of Mount Kaputa. East of the line are bedrock exposures, west are the alluvial deposits. The line is less well defined in the south, but nevertheless there is a distinct transition along the Castlereagh and Macquarie Rivers.

The highest points in the landscape are occupied by the Tertiary Volcanics (e.g. Nandewar, Liverpool and Warrumbungle Ranges).

Many of the lower-order streams appear to be aligned with the general dips and strikes. However, larger streams traverse the general structural trends. General stripping of large areas of Tertiary basalt cover and the discordance between major stream alignment and structure suggest that at least some of the larger streams are superimposed. The drainage pattern as a whole is dendritic.

Slopes are greatest in the vicinity of the basalt highlands on the eastern and southern margins and are of the order of 15° and greater. There is a marked westward increase in valley widths and decrease in valley side slopes towards the west.

The large number of interfluves that are marked by Tertiary volcanics would suggest that there was some disorganization of the regional drainage as a result of Tertiary volcanic events. Occupation of valleys with basalts and inversion of relief (e.g. Mount Panorama) support this suggestion. The effect on the Upper Darling Basin of the tectonic events is as yet not fully explained (Wellman 1971).

A large number of streams exhibit terraces, but at present there is no clear picture of the sequence of erosional/depositional events along the streams. Perhaps the historical sequence that has been defined by Warner (1967) for the Bellinger and other coastal rivers may have implications for the upper reaches of the Namoi and Gwydir Rivers. The area was probably influenced by periglacial and nivational action during the Quaternary (Galloway 1965, Bowler *et al.* 1976) but, again, the significance of the Quaternary climatic fluctuations on the basin is undefined.

Western Distributary Plain

This region is dominated by an extensive alluvial plain with an associated distributary system. The region is a large scale alluvial fan complex with apexes at the point where the streams traverse the eastern hill land margin.

LANDSAT photographs (Pl. 9) of the Namoi and Gwydir region suggest three sub-areas, namely: 1. the area of most recent stream activity and fluvial deposits; 2. older (Pleistocene?) areas of alluvial deposits; 3. an area of interaction between the Namoi and Gwydir fans.

The most recent fluvial deposits are montmorillonite-rich black clay soils, derived chiefly from the basalts of the east (Corbett 1965, Isbell 1957). The soils have considerable swelling and shrinking capacities.

Stringers of sand and gravel throughout the area suggest considerable alteration of stream courses as well as streams with sediment transport characteristics different from those of today.

The channel pattern over the whole area is a distributary system (Riley 1975). The causes of distributary and fan development are not clearly understood. However, the rapid decline in mean annual flood discharge towards the west and the rapid change in slope from the eastern hill lands to the plain suggest that the fan and channel patterns are a response to changes in energy regime in the streams.

Most of the streams emerge onto the plains of the Upper Darling Basin as wide, shallow channels. These channels are dominated by bed-load; they meander or are braided and, as with the Castlereagh River at Coonamble, are frequently bounded by large levee banks. They are typically straight to moderately sinuous with sinuosites varying from 1.1 to 1.8. These channels do shift laterally and the region between the Macquarie and Namoi Rivers is covered by remnants of wide shallow beds as mixed-load channels. Many of these still flow.

In the east of the Basin these mixed-load channels do not extend out onto the plain further than Moree or Wee Waa (Pl. 9). However, further south they extend 100 km or so out across the plains. At the downstream end of such a wide shallow channel the channel divides into numerous small distributaries as on the Castlereagh, Macquarie and Gwydir. These distributary networks are series of channels of ever-decreasing size which eventually terminate in a swamp on the alluvial plain (Pl. 10, above). The streams continue on the downstream side of these distributary

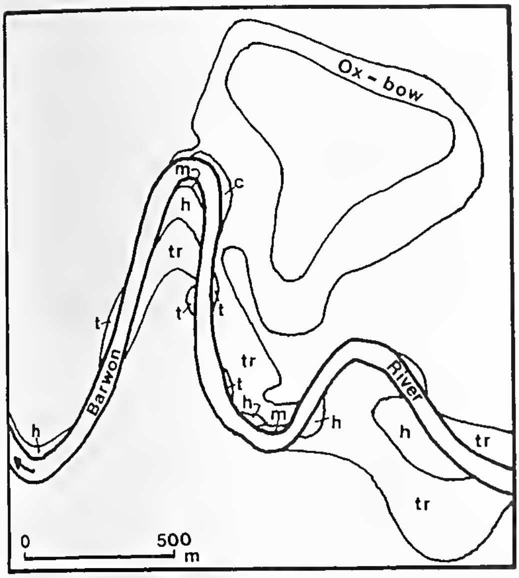


FIG.3 — A plan of the benches along the Barwon River near Walgett. Note the development of benches at the bend and also on the outside of the bend as well as along the straight reaches. Terrace (Tr), high bench (h), middle bench (m), ti-tree bench (t), and concave bank bench (c).

networks as deep, narrow, highly sinuous, suspended-load channels which contain virtually no bed-load. These streams are similar in morphology and the nature of their deposits throughout the rest of the downstream segment of the Basin.

THE DARLING-BARWON REGION

The western extremity of the basin is an area of interaction between the Barwon River, which is base level for the whole basin, and the several distributary and parent streams. The Barwon truncates the distal end of the Namoi and Gwydir fans (Fig. 2).

The region is dominated by numerous cutoffs and distributary channels oriented towards the south and parallel to the Barwon. There are numerous palaeo- and present-day ephemeral lakes in the area.

Backwater effects from the Barwon no doubt have considerable effects on the lower reaches of the eastern tributaries. With the latter rivers having bedslopes in the order of 10^{-4}, small rises of only 5 m in the Barwon can be transmitted up to 50 km upstream in the westward-flowing channels. The nature of these effects is not clear, except that stream flows and consequent sediment depositional trends can be reversed.

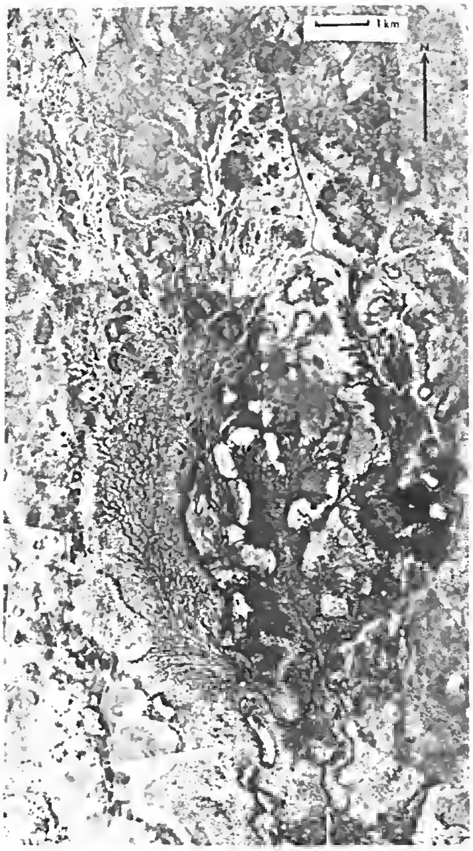
Channel Morphology of the Suspended-Load Streams: In general, the suspended-load streams are deep, narrow, highly sinuous and have steep banks with a series of depositional benches developed on them. The Barwon River at Walgett has a width:depth ratio of 8 with a mean sinosity of 2.3. The bed gradient averages 5×10^{-5} in the Darling downstream of Walgett. Bank slopes average 26° but often exceed 40°, even at depositional sites. Benches form the most prominent morphological feature aside from the narrow deep channel. Benches occur commonly at three levels (Fig. 3) along the channel: low, halfway up, and near the top of the bank (Taylor 1976, Woodyer 1968, Riley 1973, Woodyer *et al.* 1977). The benches are depositional channel features, flat, elongate and often crescentic in plan (Fig. 3). They develop at various sites along the channel, most commonly at the insides of bends as point benches, along straight reaches as straight reach or ti-tree benches, or, and less commonly, along the outside of bends as concave bank benches (Woodyer 1975). Along the Barwon near Walgett the higher two benches are very common and form a distinct and mappable surface bordering the channel (the high bench is the present floodplain of the Barwon River).

Along much of the Upper Darling and some of the suspended-load tributaries the channel is also bounded by a terrace above the high bench (Pl. 10, below). This terrace is a relic of a former regime and, although morphologically similar to the benches, is composed of entirely different sediments.

The suspended-load streams, although highly sinuous, appear to be relatively stable. The Barwon River at Walgett, for example, has not shifted its course significantly in the last 100 years (Taylor 1976). There is virtually no erosion at the outside of bends: in fact some concave bank benches are aggrading.

Deposition in the suspended-load segments of the streams is characterized by mud deposited from suspension. Taylor (1976) has reported in detail on the nature of deposits along the Barwon River near Walgett. The majority of deposition in the Barwon occurs along the banks on benches, although during major floods deposition also occurs on the terrace and across the regional alluvial plains.

Benches develop along the banks on a basal deposit or footing. These vary depending on the site along the river. At bends the footing is a point deposit of cross-bedded sands (Pl. 11, above) overlain by thin mud beds which represent mud slopes left on the flood recession. These mud beds



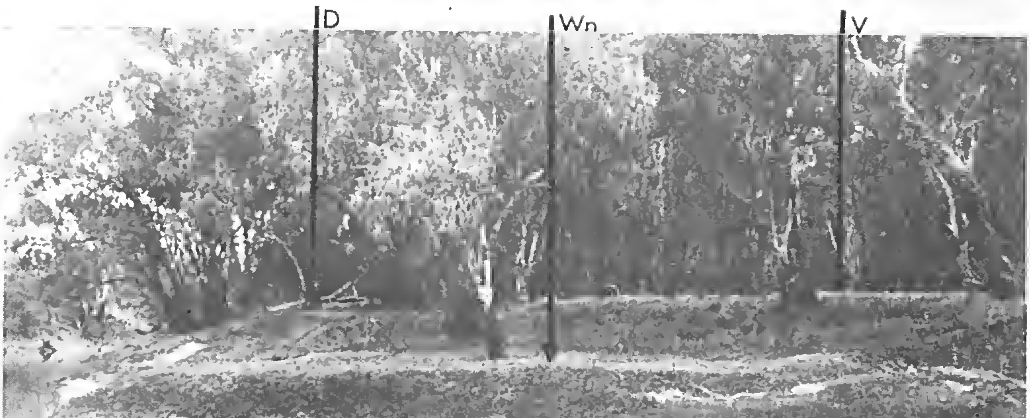


PLATE 10

(Above) A distributory marsh on Nedgera Creek between the Macquarie and Castlereagh Rivers. The flow is towards the north, the channel entering the marsh is sandy and that leaving it is muddy.

(Below) Photograph of a sequence of point benches on the Barwon River near Walgett. The lower level (Wn) is the middle bench, the intermediate level (D) is the high bench and the top level (V) is the terrace. The low sandy bench is covered by water.

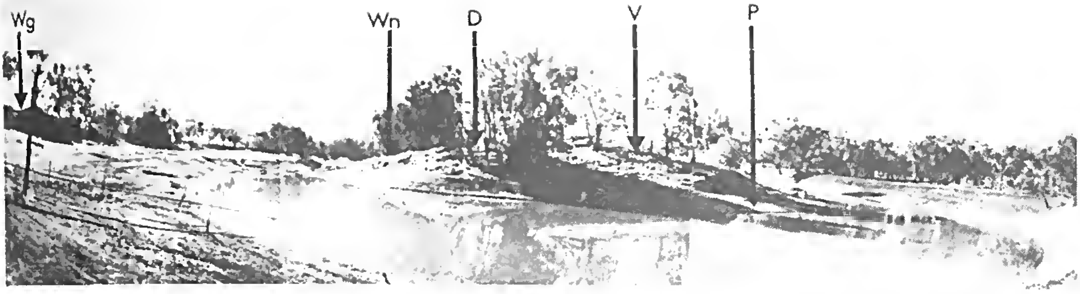


PLATE 11

(Above) Shows the same sequence of levels at another point along the Barwon near Walgett except that the low sandy point deposit (P) is illustrated. Other legend as for Pl. 10, below. Wg is the regional plain surface.

(Below) Ti-trees growing low in the channel and providing a screen behind which sedimentation occurs, gradually killing the trees and forming a ti-tree bench.

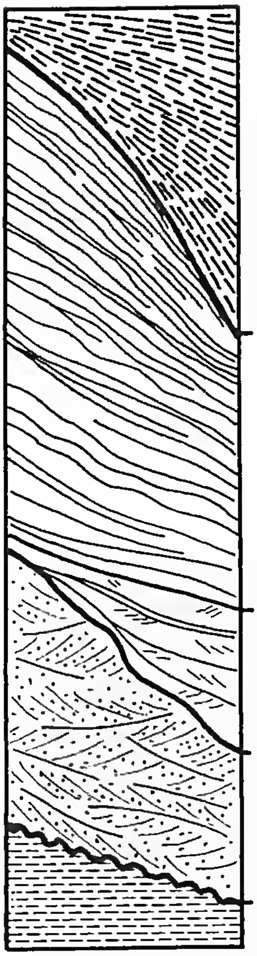


FIG. 4 — A generalized vertical profile through the bench deposits of the Barwon River.

increase in frequency up the point sand until typical bench deposits form. The height to which cross-bedded sands can be deposited is limited by the height of bedload movement. Along straight reaches and on the concave bank of bends bench footings are developed in two ways: firstly, by bank collapse resulting in a low-level mud being formed within the channel; secondly, ti-trees grow low in the channel and these tend to trap, around and behind them, sediment which provides the base for further bench development (Pl. 11, below).

The bench sediments are a sequence of inter-bedded thin sand and mud beds (Fig. 4) which are usually flat but may also be wavy. They are frequently graded and reverse-graded and lack erosional contacts. There is virtually no cross-bedding. The beds are deposited from suspension on both the top and front of the bench, producing vertically and laterally accreting, lenticular, sediment bodies along the banks of the streams. Due to the cohesive nature of the sediments deposited they suffer virtually no erosion during subsequent floods.

The continued deposition on benches causes a restriction of the channel which ultimately leads to a damming of the stream and evulsion, forming a new channel. This process is one of the major factors responsible for the large number of anabranches typical of the Darling and its tributaries in their suspended-load phases. Many of these anabranches are still developing their channels and many others are no longer active.

The Barwon at Walgett and many of the ancient suspended-load anabranches in the region have an ancestral channel associated with them. These channels deposited dominantly sandy point bars with typical scroll-bars. There is morphological evidence to suggest that the sandy ancestors and former suspended-load streams formed under different climatic conditions from those at present;

however, the sandy ancestors do not consistently show evidence of climatic control as seems to be the case in the Murray-Murrumbidgee System to the south (Schumm 1968, Bowler 1967, Bowler *et al.* 1976, Butler 1960, Pels 1964 a,b, and 1966, Langford-Smith 1960). One of us (G.T.) considers that the newly formed channels develop through a mixed-load phase prior to regressing to suspended-load deposition (Woodyer *et al.* 1977). While not denying climate change as a factor in the evolution of the Upper Darling, he suggests that evulsion and channel development due to the sedimentary processes in those channel complexes are the primary causes of channel shifting. Climate change may change the rate of development of the system and the gross channel morphology to some extent, but because of the cohesive nature of the sediment and the low gradients, the depositional character of the system is the major control.

Pilliga Sand Plain

The Jurassic sandstone area of the southern Namoi basin dominates the surface material and morphology of a region between Pilliga and the Warrumbungles. The region has a relief of approximately 500 m and slopes uniformly down towards the northwest.

The stream pattern is dendritic. Unlike streams of the distributary area which on the whole have cohesive beds, the streams of the Pilliga region are wide and sand-bedded. The peculiar sandy nature of the Castlereagh is a result of its headwaters being in this area.

The sand from the Jurassic sandstones appears to have covered a large area of the southern distributary plain and the deposits from the two sources interfinger. The Namoi west of Wee Waa is being fed by several sand bed streams from the Pilliga region.

The Lightning Ridge Region

This area is largely composed of low hill lands and has extensive areas of bedrock outcrop covered in part by silcretes and late Miocene sheet gravels (see Taylor 1978).

ACKNOWLEDGMENTS

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10

THE MURRAY VALLEY: ITS HYDROLOGIC REGIME AND THE EFFECTS OF WATER DEVELOPMENT ON THE RIVER

By B. W. BAKER* AND G. L. WRIGHT*

INTRODUCTION

The hydrologic regime of a river basin is the result of the interaction of many natural influences, such as geology and soils (discussed in other papers in this Symposium) and climate, including precipitation and evaporation. In addition, man's development of the land and water resources of a basin for his own purposes has a major impact.

The Murray-Darling River Basin is Australia's largest river system (Fig. 1). It is fed mainly by rainfall over the inland slopes of the Great Divide which form the eastern and southern borders of the Basin. Rainfall in these headwater catchments is generally reliable and the main rivers are perennial. The principal river is the Murray, which through its tributaries, drains the whole Basin. Flowing through dry country in their lower reaches the major rivers have allowed, through irrigation, intensive agricultural development in places where cultivation would not otherwise be possible. In its lower reaches the River Murray provides a major part of the water supply for Adelaide and towns to the east and north of the South Australian Gulf.

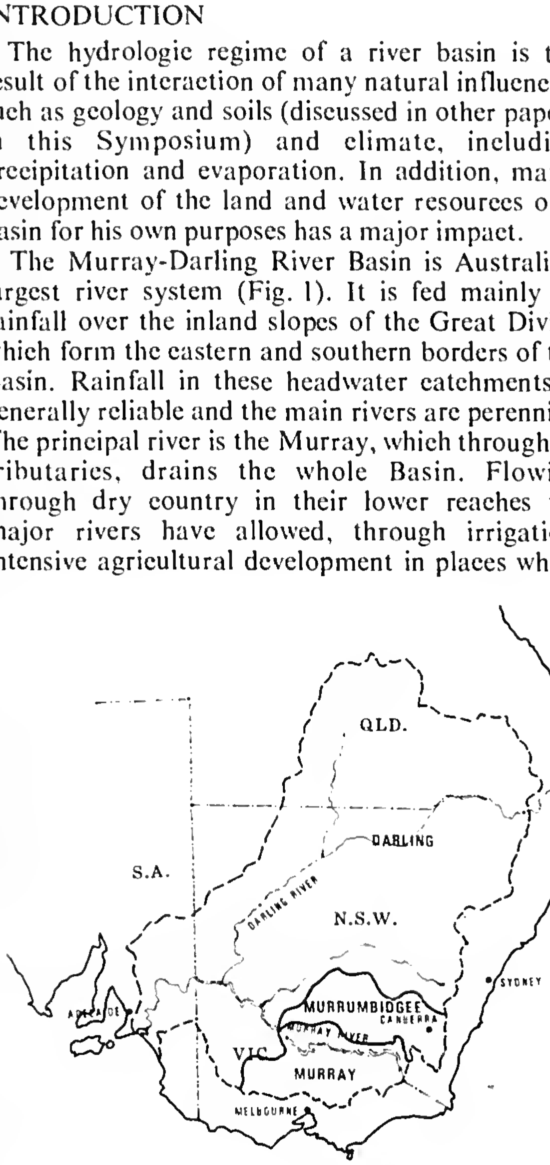

FIG. 1 — Murray-Darling Basin.

Three main groups of rivers can be identified within the Basin. The Darling and its tributaries drain the northern regions. Rainfall in their headwaters occurs predominantly in summer. Flows in this group of rivers are highly variable and the Darling itself has ceased to flow in some dry years. Although the Darling system drains over half the area of the whole Basin, its contribution to flow in the River Murray is relatively small.

The Murrumbidgee and its tributaries drain central and southern New South Wales. Median annual rainfall in the headwaters reaches 1500 mm in places, under the influence of winter low pressure systems, and the Murrumbidgee River at Gundagai has never ceased to flow over the period of record.

The River Murray itself and its tributaries upstream from the Murray-Murrumbidgee junction drain central and northern Victoria and parts of southern New South Wales. Runoff from the headwater catchments is fairly reliable and in spring includes some snow melt. Streams in this system contribute the bulk of flow to the lower reaches of the Murray.

There are other rivers in the southwest of the Basin, but they flow only intermittently.

The rivers of the Murray-Darling Basin are generally meandering and slow on the low gradients of the inland plains. The Murray and many of its tributaries have formed extensive alluvial flood plains which support the principal irrigation districts of Australia.

The flow of many rivers is regulated, especially in their upper reaches. The Murray is regulated at intervals from the Hume Dam upstream of Albury-Wodonga to the salt water barrage on Lake Alexandrina at its mouth, a distance of 2,200 km.

* Water Resources Commission of New South Wales, Box 952, P.O., North Sydney, N.S.W. 2060.

TABLE 1
PRINCIPAL STORAGES IN THE MURRAY-DARLING RIVER BASIN

NAME	RIVER	GROSS CAPACITY ($m^3 \times 10^6$)	PURPOSE
Dartmouth*	Mitta Mitta River	4000	Irrigation and hydro-electric
Eildon	Goulburn River	3390	Irrigation and hydro-electric
Hume	River Murray	3038	Irrigation and hydro-electric
Menindee Lakes	Darling River	1794	Irrigation and water supply
Burrendong	Macquarie River	1680	Irrigation and flood mitigation
Blowering	Tumut River	1628	Irrigation and hydro-electric
Copeton	Gwydir River	1364	Irrigation
Wyangala	Lachlan River	1220	Irrigation
Burrinjuck	Murrumbidgee River	1026	Irrigation

**Under construction.*

Table 1 shows the principal water storages in the Basin and their uses (WRC, N.S.W. 1971). There are many other smaller storages and overall 91% of the exploitable surface water resources of the Basin are now committed (DNR Review 1976).

This paper will deal only with the surface water hydrology of the Basin, since groundwater is covered in other papers. After a brief review of the hydrologic regime of the entire Murray-Darling System the effects of man's development of the water resources of the Murray River will be discussed.

PRECIPITATION

The Murray-Darling Basin experiences a wide range of climatic conditions. Median annual rainfall is shown in Fig. 2. To the east and south-east, where the headwaters of the major streams rise in the Great Dividing Range, median rainfalls are as high as 1500 mm but in the far west they decrease to 200 mm. In the north, rainfall is heaviest in summer; in the south, winter low-pressure systems bring the rains.

EVAPORATION

Mean annual evaporation for the Basin is shown in Fig. 3. Evaporation is high over most of the area (in excess of 1500 mm) and the trend is that as rainfall decreases, evaporation increases. In almost the whole Basin, average evaporation is greater than average rainfall. High evaporation means that losses, such as transmission losses in streams and

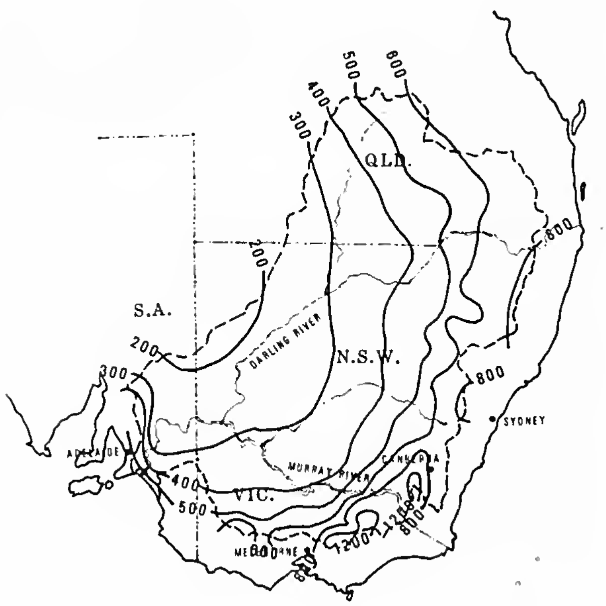

FIG. 2 — Median annual rainfall (mm).

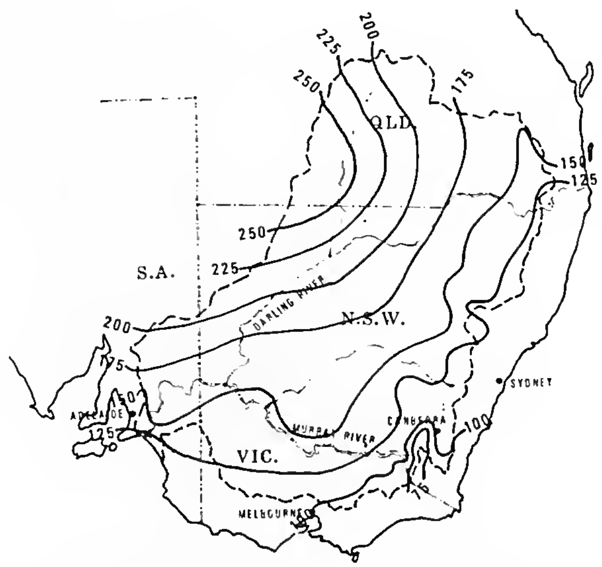

FIG. 3 — Average annual evaporation (cm).

evaporative losses from impounding reservoirs, are important factors to be considered when designing water-use systems.

STREAMFLOW

Variations in landscape, vegetation, geology and climate throughout the Murray-Darling Basin produce a variety of streamflow characteristics, varying from partly snow-fed mountain streams to ephemeral rivers. As would be expected, areas of high runoff occur where high precipitation occurs. Two of the most important factors characterising streamflow are average runoff and variability of runoff. Fig. 4 shows regions within the Murray-Darling Basin with similar runoff characteristics in terms of their amount of runoff and its variability (DND, Map Series, in prep.).

Most of the Basin has low runoff with high variability (see Fig. 4, 5d). Flows in the Murray itself are variable, but they do not reach the extremes of many of the northern rivers. At Albury the range of annual flow volumes in the Murray has varied in the ratio of about 14 to 1, from a little less than 25% of average to slightly more than three times average. The variability of monthly flows is greater, with the largest measured monthly flow at Albury being nearly 1,200 times the smallest. The average annual flow in the Murray just above Wentworth (Fig. 5) is about 9,000,000 Ml (WRC, N.S.W. 1975). At this point the total drainage area amounts to about 310,000 km^2 and the runoff is equivalent to a catchment depth of 29 mm.

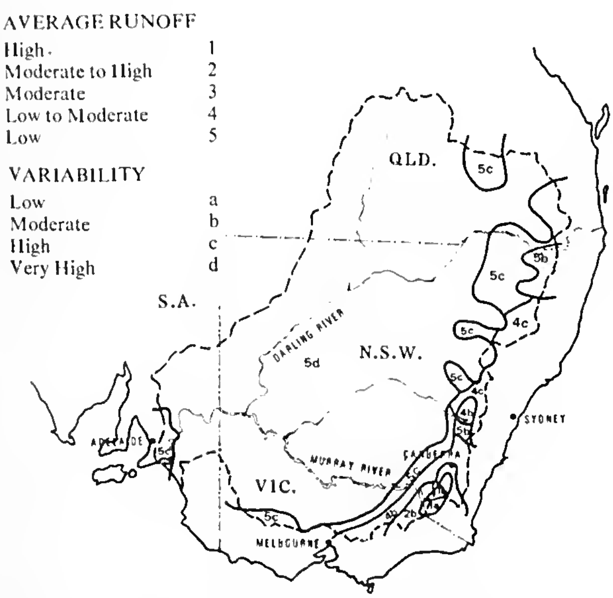

FIG. 4 — Runoff characteristics.

FLOODING IN THE MURRAY VALLEY

The degree and magnitude of flooding along the Murray River is largely controlled by the predominating terrain of each section of the valley. In the upper Murray Valley above Hume Reservoir it is confined to relatively narrow alluvial flats bordering the river along the valley floor. Below Hume Reservoir the terrain is flatter and floodwaters spill over the channel banks and inundate surrounding country. In the region between about Albury and Tocumwal, the inundation of flat land adjacent to the river channel is not uncommon. Flood flows are often swelled by contributions from the Kiewa and Ovens Rivers, which drain large areas of northern Victoria.

Near Tocumwal, a complex system of effluent creeks and anabranches leaves the Murray and carries floodwaters away from the main stream to the north. The principal streams in this system are the Edward and Wakool Rivers. Floodwaters from both the Murray and Murrumbidgee Rivers flow into the effluent system and it carries more water in times of major floods than the parent streams. This area becomes a vast inland sea during the passage of major floods and because of the slow velocities of floodwaters, periods of inundation are often lengthy.

Floods are most frequent in the winter and spring months. Table 2 shows the monthly distribution of floods recorded in the Murray River at Albury since 1865.

TABLE 2
MONTHLY DISTRIBUTION OF FLOODS

Jan.	Feb.	Mar.	Apr.	May	June
1	0	0	0	0	0
July	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
13	15	12	18	9	1

WATER RESOURCES DEVELOPMENT

The development and regulation of the water resources of the Murray River are controlled by the River Murray Commission, which was established in 1917.

The Commission administers the River Murray Waters Agreement. This provides for the construction of works at the joint expense of New South Wales, Victoria, South Australia and the Commonwealth, and the allocation of water between the

FIG. 5 — Murray Valley.

three States. The allocation entitles South Australia to receive not less than a certain volume from the upper river each year, while New South Wales and Victoria share equally the flow passing Albury, subject to provision being made for South Australia's entitlement. Each State is entitled to free use of its tributary flows entering the Murray below Albury.

The largest of the major works to date is the Hume Dam. It was first completed in 1936, was enlarged in the nineteen fifties, and now has a capacity of about 3,000,000 Ml. Dartmouth Dam, a major storage on the Mitta Mitta River, is at present being constructed and is due for completion in 1979. It will have a capacity of 4,000,000 Ml. Releases from the Snowy Mountains Scheme to the Murray River provide an additional regulated water supply.

There are very large areas in the Murray Valley, away from the main river, where topography and soils have lent themselves to large scale irrigation development. In these areas, water is brought some distance from the river in large canals for distribution into irrigation areas and districts. This type of irrigation enterprise constitutes a large part of the development in the Valley, but in addition a substantial aggregate area is irrigated by private pumping from the river.

Murray River water is also used in urban centres, the principal such usage being in Adelaide and the Iron Triangle towns in South Australia. The quantity of this usage, however, is relatively small in comparison with the total usage for irrigation in the three States.

The total diversions from the River Murray in 1974/75 were 1,560,000 megalitres by New South Wales, 1,540,000 megalitres by Victoria, and 396,000 megalitres by South Australia (RMC Ann. Rept. 1975, (1976)). These diversions are close in magnitude to the average yearly diversions over the previous ten years.

EFFECTS OF WATER RESOURCES DEVELOPMENT

Reservoirs modify the natural river regime to meet development needs. The operation of Hume Dam for irrigation has reduced winter and spring flows in the Murray and increased flows in summer and autumn. The use of water by abstraction from the river obviously reduces the long term average flow. Although a proportion of the water abstracted eventually finds its way back into the river, most of

it is used consumptively. Three main aspects of the effects of water resources development, through river regulation and water abstraction, will now be discussed.

Flooding

In providing regulated flows in the summer and autumn months, the storage in Hume Reservoir is drawn down, so that in most years space is available to store inflow during the winter and early spring months. Floods in June, July and August are often completely stored, but in the process the storage may be filled so that in years when major floods occur in the September-October period, these floods pass through the reservoir with little reduction in their peak flows.

Fig. 6 illustrates the effect that Hume Reservoir has had on the incidence and magnitude of peak flood heights on the Albury gauge in the years 1970-1975 (RMC Rept. 1977). In this period the incidence of flooding was the greatest on record. Actual peak heights are compared with those which would have occurred if Hume Reservoir had not been there.

The altered regime of river flow is also illustrated in Fig. 7 which demonstrates, by means of flow duration curves for actual and estimated natural conditions, how the natural regime has been modified (RMC, Rept. 1977).

It is clear from these figures that the operation of Hume Reservoir to meet irrigation needs has had a significant effect in reducing the incidence and severity of flooding at least in the section of the river close below it.

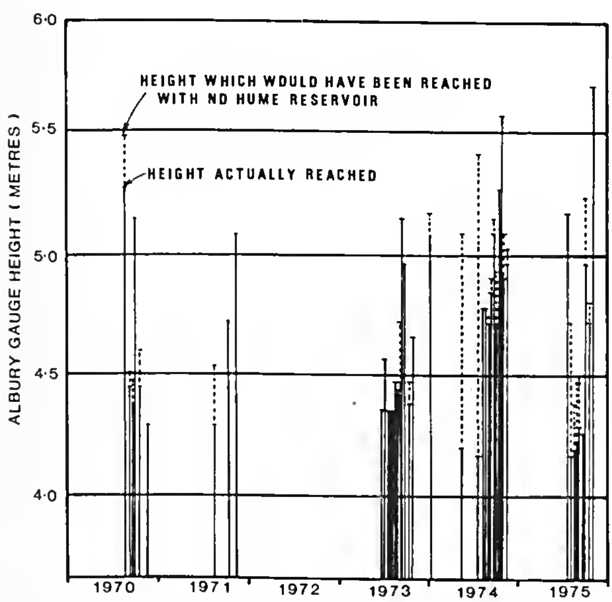

Fig. 6 — Flood heights at Albury.

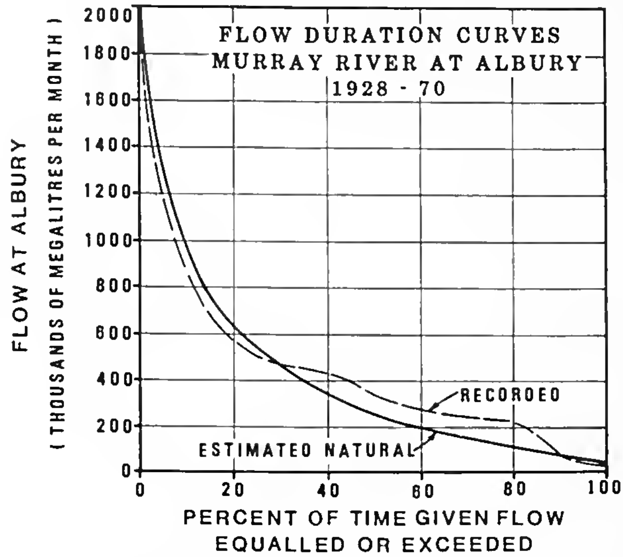

Fig. 7 — Flow-duration curves at Albury.

It is possible to achieve additional benefits by the deliberate adoption of a flood mitigation policy in operation of the dam. Although the River Murray Commission's main responsibility under the present River Murray Waters Agreement is the supply of water for irrigation and other purposes, it does provide some flood storage in Hume Reservoir, to the extent possible without prejudicing the security of water supplies.

Seasonal Distribution of Flows

To illustrate quantitatively the effects of water resources development on seasonal distribution of streamflows and long-term average flows, monthly flow records were analysed at three points on the Murray River.

The first record was the inflow to Hume Reservoir, or, prior to 1928 before the construction of the dam, the flow in the Murray at that point. The second was the flow of the Murray River at Albury and the third was the flow of the River Murray at Swan Hill.

Inflows to Hume Reservoir in the period considered are virtually unaffected by man's activities, since water abstractions above the reservoir are small in comparison to the flows. Flows at both Albury and Swan Hill, however, are affected by the reservoir upstream, and those at Swan Hill are further affected by the large abstractions from the river in both New South Wales and Victoria. Most of these abstractions take place between Albury and Swan Hill.

All three records were taken only to 1968, because later records would be affected by significant diversions into the upper Murray from the Snowy Mountains Hydro-Electric Scheme.

For each record, four different periods were analysed: first, a 'pre-Hume' period (1910-28), which represents the longest period of concurrent records under natural (or close to natural) conditions; second, a 'post-Hume' period (1929-onwards); third, a ten year period (1959-68) representing current development; and fourth, the total available record.

For each period, the means were calculated of all January flows, all February flows, and so on. The results are plotted on Figs. 8, 9 and 10 for Hume inflows, Albury and Swan Hill respectively. These figures show that for Hume inflows the seasonal pattern is nearly the same for all periods analysed. However, at Albury a considerable increase can be seen in summer/autumn flows post-Hume. At Swan Hill, the effect of abstractions upstream can be seen.

Long-Term Average Flows

To test what impact water resources development has had on long term average flows in the Murray River, a further analysis was made of the records of Hume inflows and Swan Hill flows. Two statistics were computed for each period of record: firstly the mean annual flow and secondly the Kendall coefficient of rank correlation (τ) (Kendall 1950).

The results of the statistical analysis are shown in Table 3.

The results show a definite downward trend in long-term average flow at Swan Hill as compared with the inflows to Hume Reservoir. It is noticeable that during the period 1910-1928 neither record showed significant trend. In the period 1959-1968 both records showed a downward trend (presumably because of the dry spell in the late 1960s) but at Swan Hill this was much more marked. In the 'post-Hume' period, the flows at Swan Hill showed a significant downward trend while the Hume inflows did not.

A further measure of the effects of water resources development on the long-term average flows can be seen by comparison of the 'pre-Hume'

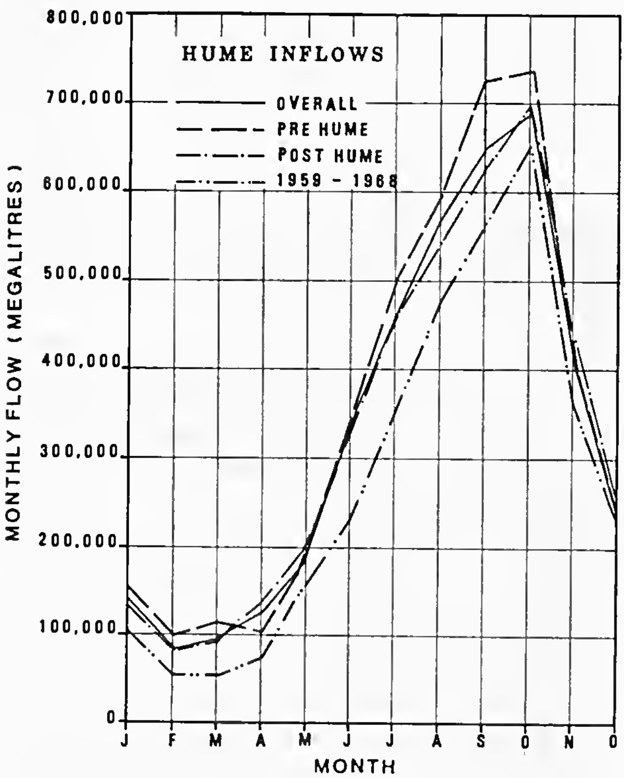

FIG. 8 — Seasonal distribution of Hume inflows.

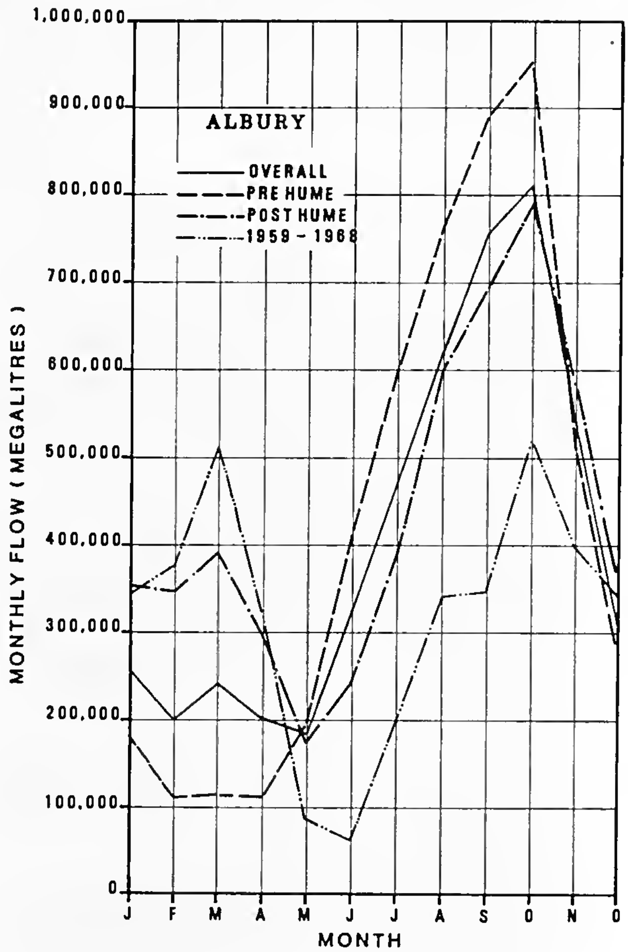

FIG. 9 — Seasonal distribution of flows at Albury.

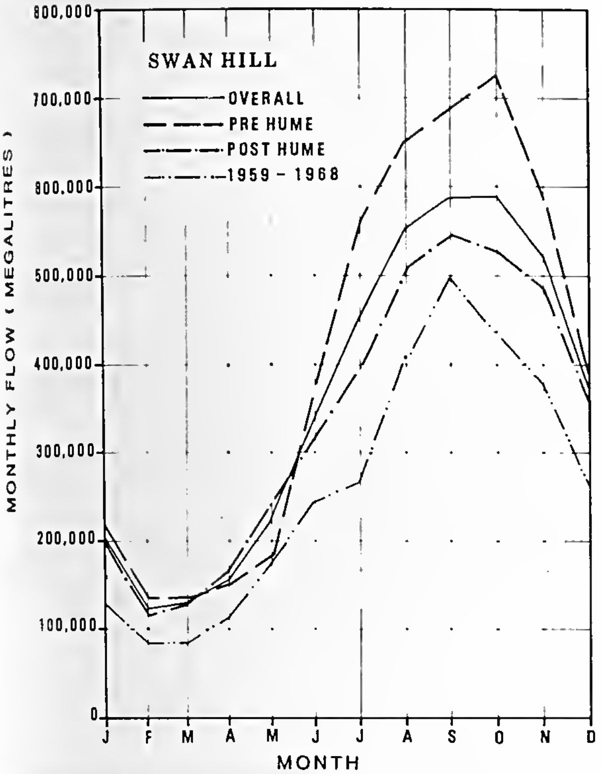

FIG. 10 — Seasonal distribution of flows at Swan Hill.

period with the period 1959-1968. At Hume Reservoir, average flow dropped to 78% of the 'pre-Hume' period during this time, while at Swan Hill the reduction was to 64%. This is clearly the effect of increased abstraction of water in the reach between Hume Reservoir and Swan Hill, and smaller inflows from the tributaries downstream of Hume, from which abstractions had also increased.

SUMMARY AND CONCLUSIONS

This paper has discussed briefly the hydrologic regime of the Murray-Darling Basin, with emphasis on the Murray River. It has then outlined the development of the water resources in the Murray River and attempted to determine quantitatively the effects of that development on the surface water hydrology of the river, by the use of simple statistical tests.

The results have shown the following:

(i) Simple statistical analyses can be used to determine, in quantitative terms, the effects of water resources development on hydrologic regime. This analysis confirms what is known qualitatively about these effects, but is difficult to assess because of uncertainties about return flows to the river, effects of groundwater and so on.

(ii) Water resources development has had a beneficial effect on flooding in the valley, by reducing the magnitude of many floods through regulation of the river flows.

(iii) Regulation and abstraction have altered the seasonal distribution of streamflow to a certain extent by relatively reducing the winter and spring flows and increasing the summer and autumn flows. The effect differs in different reaches of the river. It is very apparent close below Hume, but less marked further downstream, where tributaries add to the winter/spring flows and abstractions for irrigation reduce the summer/autumn flows.

(iv) Development has reduced the long-term average flow at Swan Hill, which is downstream of the major diversion points on the Murray River. There has been a significant downward trend in flow volumes since construction of Hume Reservoir and this trend is continuing.

TABLE 3
RESULTS OF STATISTICAL ANALYSIS

HUME				SWAN HILL			
Period of Record	Mean Annual Flow (a)	(b)	Kendall τ (c)	Period of Record	Mean Annual Flow (a)	(b)	Kendall τ (c)
1910-1928 (d)	4212	100		1910-1928 (d)	4788	100	
1929-1968	4039	96		1929-1970	3974	83	—0.054
1959-1968	3299	78	—0.093	1959-1968	3053	64	—0.162
1891-1968	3991	95		1910-1970	4228	88	—0.082

(a) Mean annual flow in Ml x 10^3. (b) Mean annual flow expressed as a percentage of that for the 'pre-Hume' period. (c) Only values significant at the 5% level are shown. (d) 'Pre-Hume' period.

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THE PRESENT SALINITY POSITION IN THE RIVER MURRAY BASIN

By K. O. COLLETT*

ABSTRACT: It is desirable that the salinity of water supplied from the River Murray should not often exceed 800 EC units. This is approximately the limit for irrigated stonefruit and overhead sprayed citrus, and for domestic use. In dry years this level of salinity has been exceeded in the lower reaches of the river.

The effect of river impoundment and diversion has been to reduce *average* flows to South Australia, so raising the salinities experienced in most years. In the post-Darmouth era, diversions will be increased by only a relatively small percentage.

Regulation of the river by storages, by ensuring reasonable flows, has removed the threat of experiencing extremely high salinities in *drought* years, as was the case with the river unregulated. Dartmouth will further improve this situation.

River salinity records obtained at Mannum (S.A.) since 1941 show a rising trend, which, although hard to quantify, indicates a possible increase in salt accessions each year of about 11,000 to 25,000 tonne/year. This trend is obviously due to irrigation activities causing increased salt returns to the river. Catchment deterioration could also be playing a part.

Some works to reduce salt accessions to the river have already been undertaken. These have tended to be at sites where large reductions have been gained with modest expenditure. Further interception and diversion schemes will generally be less effective in terms of tonnes of salt diverted per dollar spent.

The extensive irrigated regions in New South Wales and Victoria are experiencing a rapid increase in the area with high water tables, which cause salinisation of surface soils. If unchecked this will have a serious effect on the productivity of the regions, and their ability to support decentralized populations will decline. Some proposals to control the problem have been put forward, but disposal of saline groundwater from works which might be undertaken is a major problem. A scheme proposed by the Victorian Water Commission for part of the Shepparton Region would involve disposal of some moderately saline groundwater to the River Murray, with subsequent offsetting of the rises in river salinity by increased diversion of Barr Creek and evaporative disposal in Lake Tyrrell. New South Wales and South Australia have indicated that they do not agree with the concept of using the Barr Creek/Lake Tyrrell scheme only to restore 'status quo' salinities.

All three States are now moving towards a joint consideration of the total salinity problem in the Murray Basin, with a view to producing co-ordinated strategies for salinity control.

INTRODUCTION

The River Murray functions both as a source of supply and as a drainage course for a large part of northern Victoria and southern New South Wales, and is the major source of water supply in South Australia.

There are two distinct aspects to the question of salinity in the Murray Basin. The first is the salinity of water supplied from the river, whilst the second is the salinisation of irrigated land caused by the development of high water tables.

This paper reviews the current situation and makes some forward projections. Necessity for future co-ordination of the salinity control strategies of all three States is highlighted.

In August, 1967, the River Murray Commission engaged the consulting engineering firm of Gutteridge, Haskins and Davey to carry out a comprehensive investigation of salinity in the Murray Valley. The report of the study was published in 1970. In this paper reference is made to Gutteridge, Haskins and Davey as the

* Designing Engineer, State Rivers and Water Supply Commission, 590 Orrong Road, Armadale, Victoria 3143.

Consultants. New South Wales and Victoria are termed the upper States (relative to the direction of flow of the Murray River).

Salinities have been expressed in terms of electrical conductivity at 25°C (microsiemens/centimetre), commonly known as EC units. Salinities in mg/l or p.p.m. were converted to EC units where necessary by dividing by 0.6. The unit megalitres/day has been used for instantaneous flow rates, and also some average flows have been expressed in this unit, which is easier to relate to conditions on the Murray River.

SALINITY LIMITS FOR ESTABLISHED USES

Before studying salinity levels along the Murray River, it is desirable to consider salinity limits for established uses, to serve as comparative levels. It is recognized that there is really no sharp division between acceptable and unacceptable salinities, and that economic losses increase steadily as salinity rises. Nevertheless, there are salinity levels which, if exceeded, would be cause for concern, and these are referred to in this paper.

The salinity of water supplies can be a problem in all three States, but especially in South Australia, where the major uses are (a) irrigation of high value horticulture and (b) domestic and industrial water supply. For the horticulture, which comprises citrus, stonefruit and vines, the Consultants gave two salinity limits, one based on a consideration of the effect in the root zone of the total dissolved salts, the other on the effect of the chloride content. This latter limit was converted to a limit in terms of total salinity by using a ratio of chloride to total salts of 0.4. The Consultants' recommendations (which have been converted here from TDS to electrical conductivity values) are given in Table 1. The significant value in the Table is the limit of 725 EC units for stonefruit.

In addition to the limits in Table 1, which assume that furrow or low-throw sprinkler application is used, there is another limit for citrus (and stonefruits) watered by overhead sprays, as it has been shown that chloride uptake by citrus trees is greater with this mode of application. It has been suggested that the appropriate salinity limit for overhead sprayed citrus is 800 EC units (Magarey 1977).

Almost 50% of the South Australian horticultural plantings are citrus and stonefruit and a significant proportion of these plantings have overhead sprays. From the foregoing, it is therefore apparent that salinities in the range 725 to 800 EC units mark the limit of acceptability for a large part of the South Australian irrigated areas.

For domestic use the desirable maximum salinity is 835 EC units (Gutteridge, Haskins & Davey 1970, E.W.S.D.(S.A.) 1976). The domestic aspect particularly concerns South Australia, where Murray water not only supplies towns along the river but also augments the water supply to most other towns and cities. In Adelaide, Murray water has averaged one quarter of the total supply in recent years, and in the 1967/68 drought year 80% of the water consumed in Adelaide came from the Murray. As urban populations grow, augmentation from the Murray will become increasingly important.

For the purposes of this paper, limits for horticulture and domestic supply have been rounded off to give, as the river salinity level which should not often be exceeded, a common value of 800 EC units.

TABLE 1
LIMITING VALUES OF SALINITY FOR WATER SUPPLIED TO HORTICULTURE
(expressed in terms of EC units)

Based on:	Citrus	Stonefruit	Vines
Consideration of effect of total dissolved salts	1000	1000	1750
Consideration of effect of chloride content	1100	725	1450

SALINITY ALONG THE RIVER MURRAY

LONGITUDINAL SALINITY PROFILE

River salinities from Hume Dam to the mouth are measured regularly, and Fig. 1 shows the arithmetic average of these salinities at points along the river for a recent four-year period with a typical range of flows (solid line) and for a 10-month dry period (dashed line) when, for most months, flows to South Australia were down to levels of entitlement under the River Murray Waters Agreement (Appendix A). Both these longitudinal salinity profiles have a similar shape, with salinities higher in the dry period.

Both profiles show that the river salinity is low until the Loddon River confluence is reached. Here water from Barr Creek, which is the main drain of a surface drainage network serving about 125,000 ha of salt-affected farmland in the Kerang Region, enters the Murray. It is the biggest point source of salt along the river, and as shown in Fig. 1, causes a marked salinity jump. It should be noted, though, that works which have been constructed to divert Barr Creek flow to nearby Lake Tutchewop for

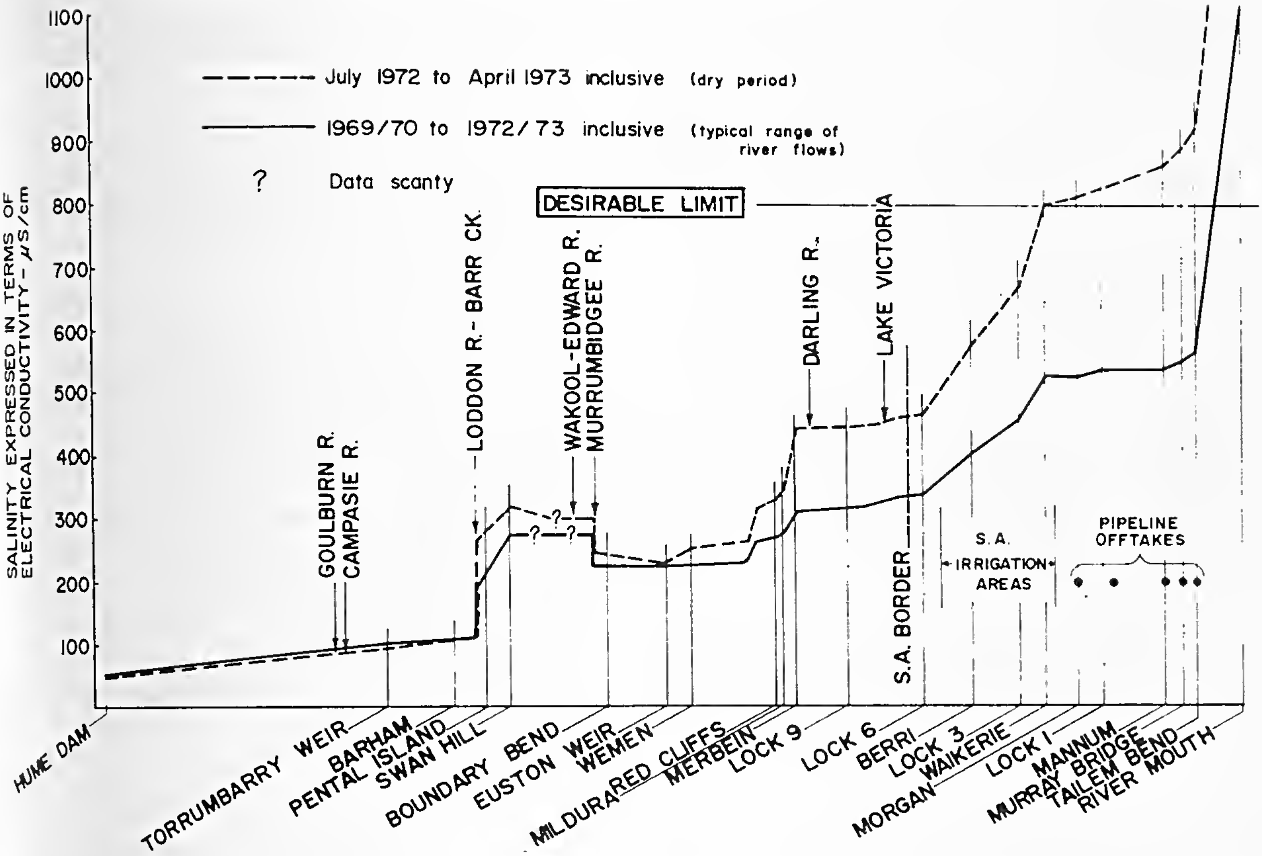

FIG. 1 — Longitudinal Salinity Profiles.

evaporative disposal, although limited by evaporative capacity to only about 15% of the creek flow in the long term, can divert much larger proportions in dry periods, and can significantly reduce the salinity jump.

A further rise is shown occurring between the Loddon River confluence and Swan Hill. This is due, in part, to some of the Barr Creek salt load not joining the mainstream until just upstream of Swan Hill.

The next major input is from the Wakool River, which carries a salt load about half that of Barr Creek. The main source of salt in the Wakool appears to be groundwater which seeps in along the deeply incised lower reaches (Gutteridge, Haskins & Davey 1970). Its contribution to river salinity can be masked by significant flows of Murray water passing down the Edward River and diluting Wakool flows before they join the Murray.

Proceeding downstream, a significant diluting effect due to the Murrumbidgee River flow is noted.

Major salt accessions occur just upstream of Red Cliffs, and in the 20 km between Mildura and Merbein. The latter accession is the result of groundwater seepage from mounds built up beneath irrigated areas.

Another concentrated groundwater accession occurs between Locks 6 and 9, where Lake Victoria, an offstream storage, has raised groundwater levels adjacent to a number of side channels of the River Murray.

The major South Australian irrigation developments adjoin the River Murray in the Lock 6 to Waikerie reach. Here, as Fig. 1 shows, substantial increases in river salinity occur. Some of the causes of this are:

(a) irrigation induced accessions in the form of seepage from mounds beneath irrigated areas, seepage from drainage evaporation basins, or drainage basin overflows,
(b) subsurface flows brought about by hydraulic gradients created by weirs and locks,
(c) natural groundwater inflow.

Downstream of the principal irrigated areas the salinity rises further, but at a lesser rate, to Tailem Bend. Beyond this point, evaporation from Lakes

Alexandrina and Albert increases the salinity dramatically.

It can be seen from Fig. 1, that in the 10-month period selected for study, the average river salinity towards the downstream end of the South Australian irrigated areas approached the limit of 800 EC units. Moreover, at the principal urban supply pipeline offtakes further downstream, this limit was exceeded by up to 125 EC units.

River Murray salinity levels are therefore of great concern to South Australia, especially as salinities can be higher than the averages given in Fig. 1. For example, at Morgan, which is just downstream of the irrigation developments, and which is also the site of the first major pipeline offtake, the average monthly salinity equalled or exceeded 900 EC units for four of the months in the 10-month dry period, compared with the average for Morgan of 814 EC units.

Relationship between Flow and Salinity

In the upper reaches of the river its salinity is derived from rock weathering, and does not vary much with flow. This is illustrated by the curve of salinity versus flow for Torrumbarry in Fig. 2.

The accessions further downstream tend to maintain a salt load input which, generalizing broadly, remains constant regardless of river flow variations. In the lower reaches, therefore, river salinity rises as flow decreases, and *vice versa*. The curve for Lock 6, at the South Australian border, shows this (Fig. 2).

It is of interest to study the average flow at a number of points along the river for the 10-month dry period July 1972 to April 1973. These are set out in Table 2. The diluting effect of the Murrumbidgee River is clearly shown by the increase in flow between Wakool Junction and Boundary Bend. It will also be noted that a large flow disappears between Lock 1 and the Murray River mouth. Diversions in this reach, including those to Adelaide, account for only 10%. The major loss is accounted for mainly by evaporation from the lakes at the mouth. This evaporation, which is estimated to average about 2,000 Ml/d, and which has been allowed for in the established river regula-

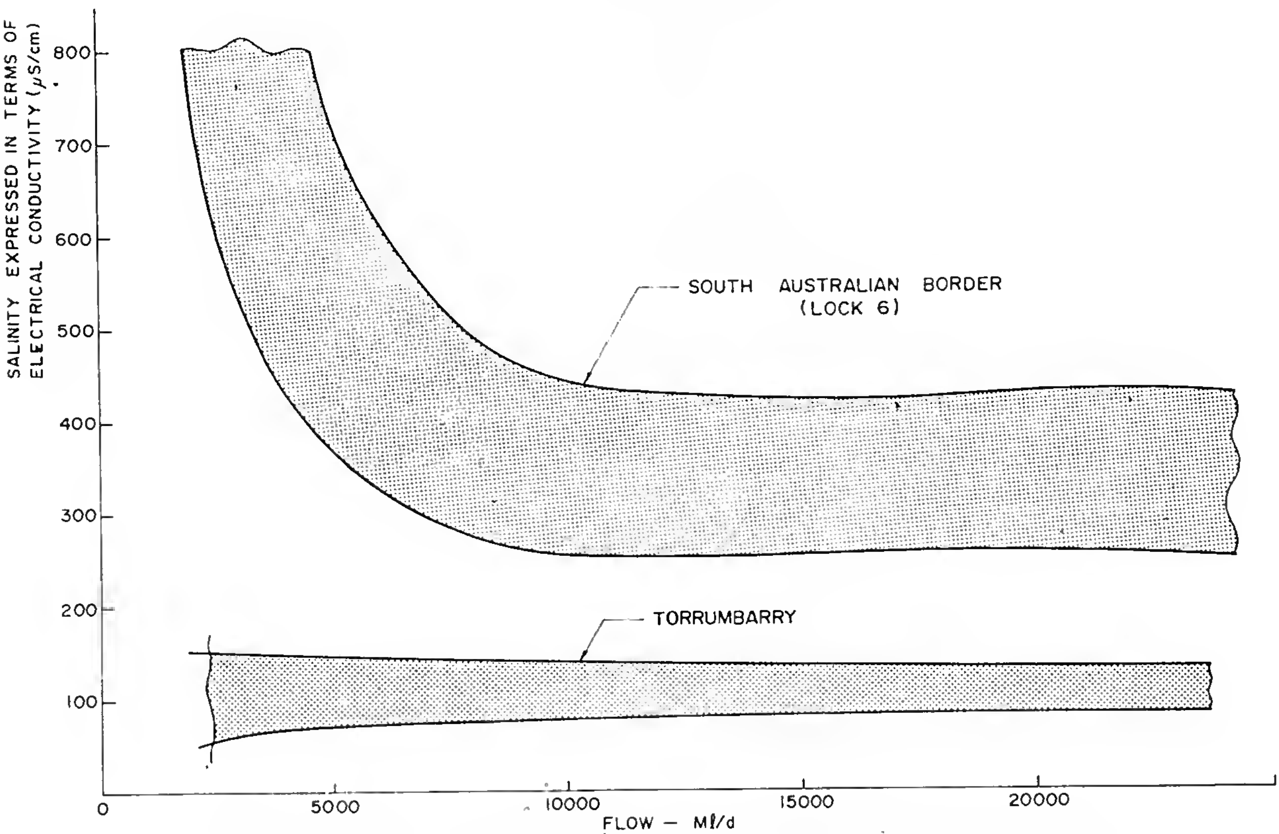

FIG. 2 — Salinity versus Flow at Torrumbarry and the South Australian border.

TABLE 2
AVERAGE FLOW IN RIVER MURRAY JULY1972 TO APRIL 1973

Station	Average Flow (Ml/d)	Major Tributaries	Major Offtakes
Heywoods	11,000		
		Kiewa River	
Doctors Point	12,000		
Corowa	11,800		
		Ovens River	Mulwala Canal Yarrawonga Main Channel
Yarrawonga	9,000		
Tocumwal	8,300		
			Edward River
Barmah	5,200		
		Goulburn River Campaspe River	National Channel
Torrumbarry	5,400		
Barham	5,300		
		Loddon River/Barr Ck.	
Swan Hill	4,800		
		Wakool/Edward River	
D/S Wakool Junct.	5,300		
		Murrumbidgee River	
Boundary Bend	6,800		
Euston (Lock 15)	6,600		
Colignan	6,500		
		Darling River	
D/S Rufus River	6,000		
Lock No. 1	3,500		
River Mouth	250 approx.		

tion practices, effectively provides a diluting flow through to the lowermost reaches of the river.

EFFECT OF RIVER REGULATION ON SALINITY

Before significant diversions and impoundings began along the Murray River, the average annual flow to South Australia was about 12 million megalitres. (Some other estimates are higher, i.e. about 15 million megalitres.) Usage by the two upper States has now reduced this by more than half. What has been the effect on salinities in South Australia?

Fig. 3 shows both the monthly pattern of natural flow to South Australia (Heliwell 1963), and the present average monthly flows for a typical sequence of years (1967/68 to 1972/73). It will be noted that the activities in the upper States have resulted in large flow reductions in winter, spring and early summer. However, for a year in which flows approximate to the present winter-early summer flows of Fig. 3, salinities would be acceptable. Taking December as an example; average natural flow was about 50,000 Ml/d, whereas flow now averages a little over 15,000 Ml/d. From Fig. 2, it can be seen that for flows at the border in excess of 10,000 Ml/d, salinities are generally low enough (300 to 400 EC units) to be of no concern to users, even with increases due to accessions further downstream. In post-flood situations, however, high downstream salinities can result from return flows of saline water from bank storage (see later, Effect of Flood Flows) even when salinities are in this range at the border.

Average flows have been reduced also during late summer and autumn, but again, for a year with flows approximating to the present flows of Fig. 3 salinities would be within acceptable limits, with the possible exception of January.

While average conditions are satisfactory, conditions in individual years may not be. A computer program developed by the River Murray Commission has enabled the operation of the present river system to be simulated for a period with the climatic and hydrologic conditions of 1895/96 to 1971/72. The results of this simulation have been used to prepare Fig. 4, which shows the

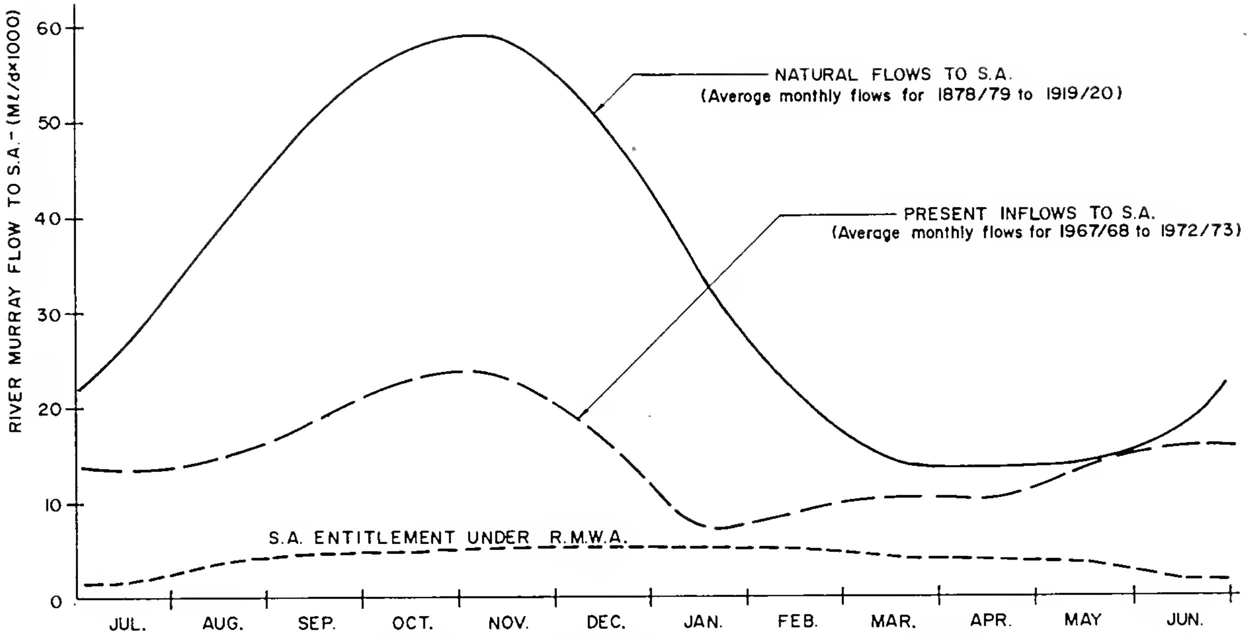

FIG. 3 — Effect of River Murray Regulation on Flow — average year.

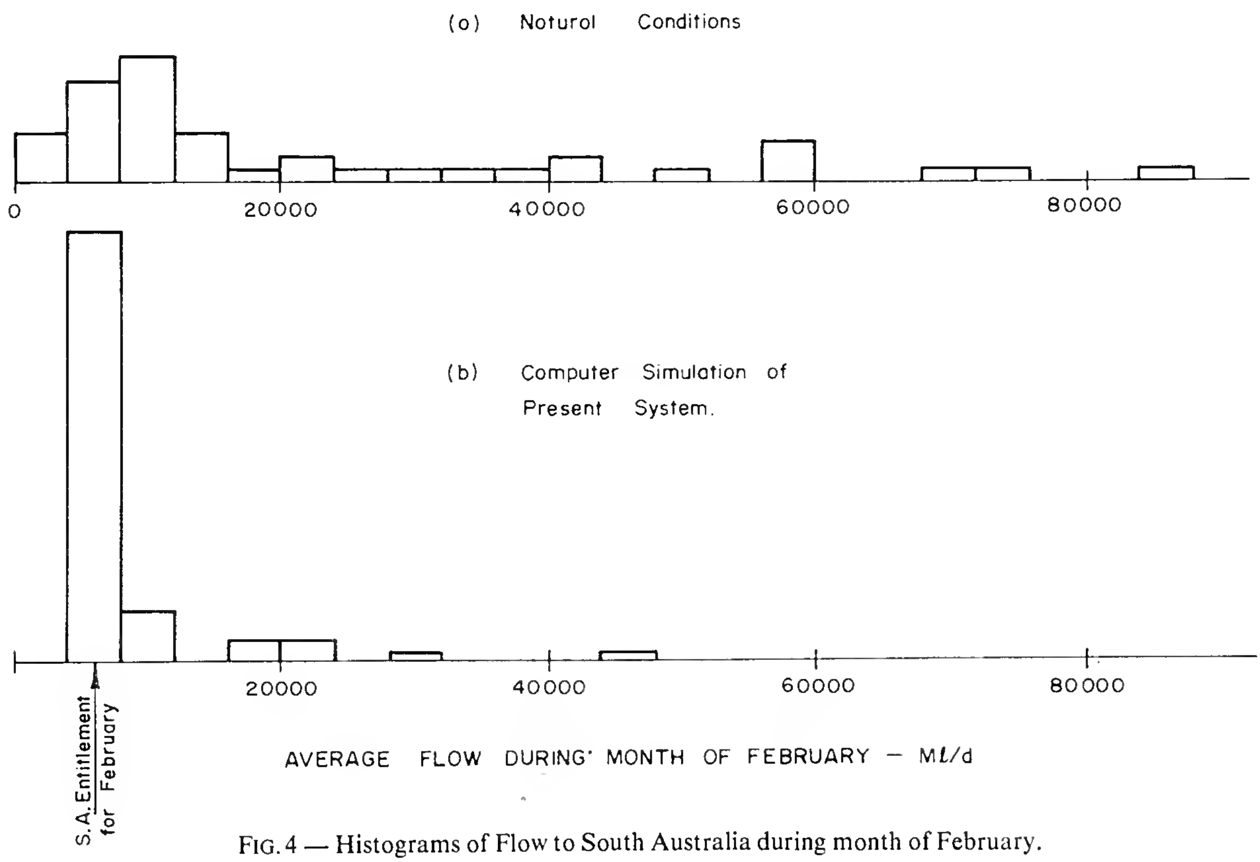

FIG. 4 — Histograms of Flow to South Australia during month of February.

distribution of flows to South Australia for the month of February, with the present degree of regulation and usage by the upper States. The distribution of natural flows is also shown for comparison. The figure illustrates the greater tendency for the present flows to lie towards the statutory entitlement, that is, towards the low flow end of the scale. Although February is used as an example, this pattern is repeated throughout summer/autumn, and to a lesser extent in winter/ spring. With flows to South Australia equal to the present statutory entitlement, salinities in that State can, and do, exceed the limit of 800 EC units.

Flow reductions at the South Australian border due to the Dartmouth storage will not be great. The role of this reservoir is basically to safeguard existing development, and the average increase in diversions by the upper States will be in the order of only 0.5 million megalitres per year. This represents a 14% increase in the total annual diversion (averaged over the six year period from 1969/70 to 1974/75) from the River Murray, tributaries above Albury, and effluent streams below Albury.

However, one trend could be significant. In the past, uncommitted flows in the Murrumbidgee River have played an important role in providing dilution of the lower sector of the Murray. But irrigation development along that river in recent years has brought its water resources close to full commitment. The dilution potential of the still uncommitted flow is now regarded as only marginal during periods of high irrigation demand. This situation would be accentuated if additional en route Murrumbidgee storages were to be constructed.

One very notable effect of river regulation is the improved situation in *drought* years. For example, under natural conditions, in 1914/15, flows to South Australia dropped almost to zero, and river salinities of 7,000 EC units were recorded at Berri, rising to 10,000 EC units at Morgan, and 16,000 EC units towards Lake Alexandrina. The River Murray Commission computer simulation shows that with present storages and demand levels, and with a repeat of 1914/15 conditions, inflows to South Australia could be held at about 4,000 Ml/d for most months, as depicted in Fig. 5. Although salinities for much of the South Australian reach would be above the 800 EC limit under these flow conditions, the improvement over natural conditions is nevertheless dramatic. The further increases in flow under post-Dartmouth conditions, which have also been computer simulated, and which are shown in Fig. 5 for 1914/15, are the result of:

(a) An increase in the South Australian entitlement, under the River Murray Waters Agreement, from 1.55 million Ml/year to 1.85 million Ml/year. This will have to be made available by the upper States unless a 'period of restriction' is declared.

(b) With Dartmouth in operation 'periods of restriction' could be less frequent, even with the increased South Australian entitlement. (Appendix A explains the meaning of the term 'period of restriction'. With the present degree of regulation and usage, the simulation showed that in a repeat of the period 1895/96 to 1971/72 (77 years), there would have been 18 years of restrictions).

The diluting effect of Dartmouth flow is particularly noticeable in December 1914 and January 1915 in the simulation. In these months, flow would be increased from 4,500 Ml/d to 7,000 Ml/d, and salinity at the border would reduce from about 600 to 400 EC units.

In short, the effect on the South Australian reaches of diversions and impoundings in the upper States has been to narrow the range of flows and salinities experienced.

Salinity Trends

Annual values of salinity recorded at Mannum (S.A.) since 1941 show a rising trend of about 6 EC units/year, which is repeated in the five year moving average values (Toll & Trewhella 1977). In an average annual flow of (say) seven million megalitres, this represents a salt load increase of about 25,000 tonne/year, every year. It should be noted, though, that some part of the rising salinity trend could be attributable to increasing diversion of low salinity water for irrigation.

The figure for the rate of salinity increase must be treated with the greatest caution, as the position of drought years (high salinity) and flood years (low salinity) in the sequence has a great effect. One means of eliminating this effect is to consider salt loads for periods of (say) 10 years early in the sequence of years and towards its end. For the period 1963-72 the Mannum salt load (calculated using average annual values of flow and salinity) was 1,500,000 tonne greater than for the period 1941-50, even though the flow for 1963-72 was 15 million megalitres less than for the earlier period. It is reasonable to assume that had there been an additional flow of this amount, it would have comprised water from the upper catchments at about 70 to 170 EC units salinity, carrying a salt load of 1,000,000 tonne (say). Therefore, for equal flow volumes in the two 10-year periods, the difference

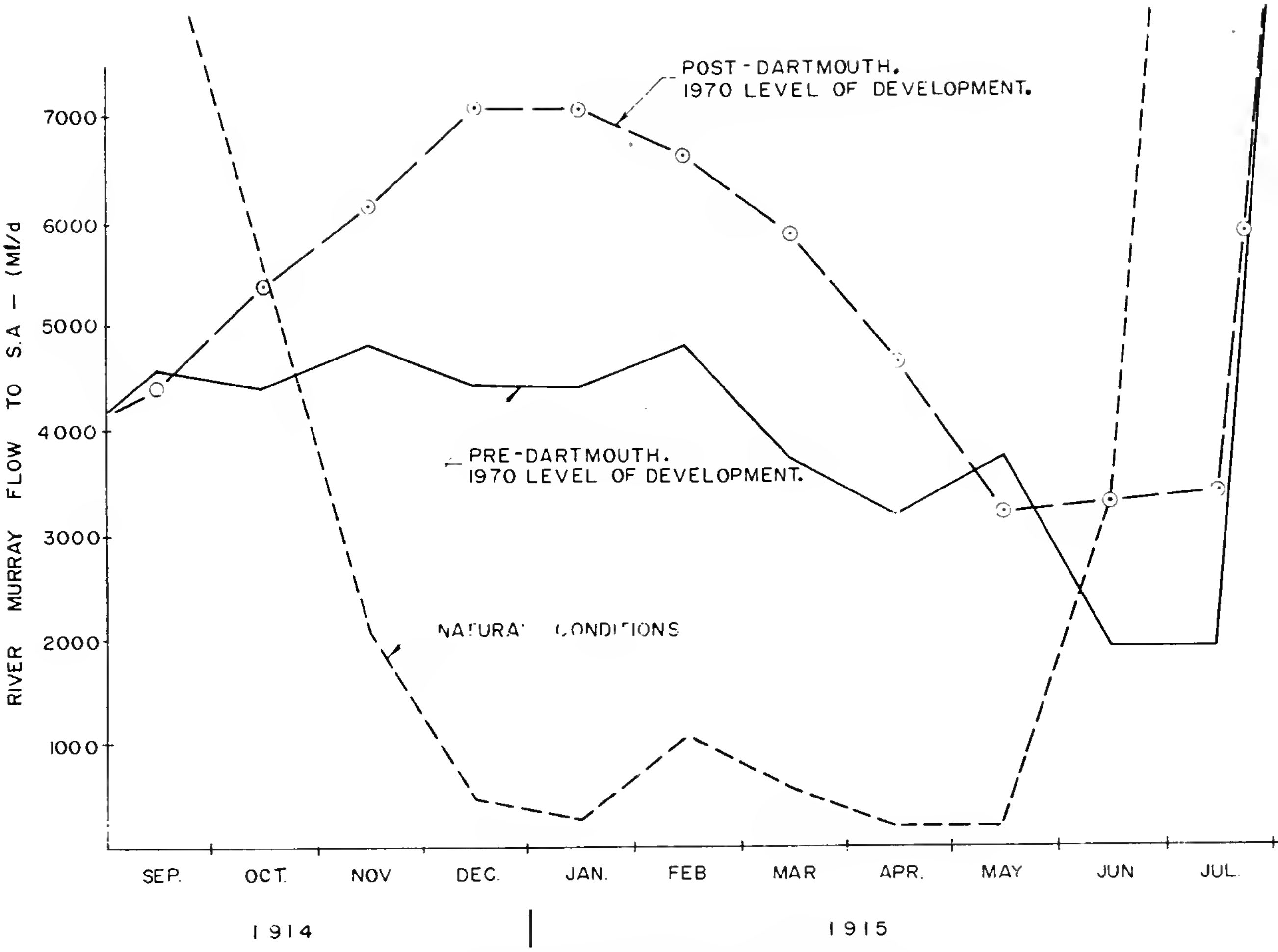

FIG. 5 — Effect of River Regulation on Flow — 1914/15.

in their salt loads would be about 2,500,000 tonne, that is, in one year the average salt load carried would be 250,000 tonne more in the latter period than in the former. Given that the mid points of the two periods are 22 years apart, it appears from this analysis that new accessions have been developing at the rate of about 11,000 tonne/year. Again, caution is necessary, as consideration of different periods can give quite large variations in the rate of increase of salt load. Nevertheless, it is clear that there has been a significant increase in salt load inputs in the last 35 years. Possible reasons for this are given later.

Effect of Flood Flows

The salinities for the years 1957 and 1958 highlight an interesting phenomenon. Flows in these years were not unusually high or low, being 5.9 and 9.9 million megalitres respectively, at the South Australian border. In such years average Mannum salinities would normally be 350-400 EC units. However, in 1957 the average Mannum salinity was 660 EC units while for 1958 it was 780 EC units. The explanation advanced is that 1956 was a year of prolonged flooding in which the river flow to South Australia totalled 54 million megalitres. This is believed to have caused extra storage of saline groundwater adjacent to the river, with consequent higher-than-normal accessions for some time after the flow recession.

Similar high salinities were noted following 1974, in which flow to South Australia was 35 million megalitres.

WORKS TO CONTROL SALINITY

The last 10 years has seen an increased awareness of the effects of high river salinities, with some works being undertaken specifically to reduce accessions. The extreme situation in the drought year of 1967/68 was one of the catalysts. Another was possibly the unfavourable economic forces

TABLE 3
WORKS TO CONTROL SALINITY
(For a brief description of these works, refer to Appendix B)

Scheme	*Date of Construction*	*Capitalized Cost*[1]	*Tonne salt/year diverted*	*Capitalized Cost/ Tonne/year*
Lake Victoria/Brilka Creek, Stage I (S.A.)	1967[2] (Temporary)	\$90,000	27,000[3]	\$3
Barr Ck./Lake Tutchewop (Vic.)	1968	\$2,250,000	30,000	\$75
Lake Hawthorn (Vic.)	1968	\$1,735,000	11,000[3]	\$157
Curlwaa I.A. (N.S.W.)	1973/74	\$80,000	11,000	\$7
Renmark Reservoir (S.A.) Stage I	1976/77	\$60,000	24,000	\$3
Mildura-Merbein Groundwater Interception (N.S.W. side)	Under construction	\$625,000	27,000	\$23
Mildura-Merbein Groundwater Interception (Vic. side)	Construction imminent	\$1,235,000	25,000	\$49
Noora Basin (S.A.) (Serving Renmark, Berri-Barmera, Cobdogla areas)	Possible scheme	\$20,000,000	(a) 75,000 currently[4]	\$267
			(b) 130,000 in Year 2000[4]	\$154
Lake Tyrrell Scheme (Vic.)	Possible[5] Scheme	\$30,000,000	100,000[6]	\$300

Notes:
[1] Annual costs capitalized at 8% have been added to capital cost. Capital cost updated to present day level where necessary, assuming 10% inflation rate.
[2] Temporary works constructed in 1967. Capitalized cost refers to permanent works constructed in 1976.
[3] As well as diverting salt away from the river this scheme delays salt entry to the river until flows are adequate to dilute it.
[4] Maximum values. Lesser values apply in many years.
[5] The Victorian Water Commission has proposed that the Lake Tyrrell Scheme be constructed to offset the effect of outfalling Shepparton Region groundwater to the river.
[6] Additional to present diversions.

affecting agriculture generally, which could have made production losses more important to growers.

As might be expected, the situations where the maximum interception of salt can be gained per dollar spent have been tackled first, although some of the more cost effective measures have been implemented later because of the amount of investigation needed before proposals could be formulated.

Table 3, which lists the control works undertaken to date, shows the significant benefit obtained at modest cost so far. Also, two projects which might be undertaken are included to illustrate the higher costs of future works.

The schemes installed to date, together with those about to be constructed, have a combined salt interception capacity of 155,000 tonne/year. Assuming this was distributed evenly throughout the year, the combined effect with a river flow averaging 6,000 Ml/d past the sites of the schemes, as it did in the 10-month dry period reported earlier in this paper, would be a reduction in salinity of 120 EC units. Although this calculation is over-simplified, in that it ignores the effect of diversions, drainage returns, and inputs from the Darling River and Lake Victoria, it does suffice to show that the present works, together with those about to be constructed, can be a significant factor in maintaining acceptable salinity levels.

On a more pessimistic note, estimates (see earlier, Salinity Trends) for increases in salt accessions to the river are between 11,000 and

25,000 tonne/year. If increases are still occurring at this rate, the benefit of the 155,000 tonne/year capacity of the schemes will soon be nullified.

IRRIGATION AREAS IN THE UPPER STATES

So far this paper has concentrated on salinity from the point of view of the user of River Murray water for supply. This section covers the other major aspect, namely waterlogging and salinity problems brought about by high water tables beneath irrigated lands in the Murray Basin.

In Victoria and N.S.W. there are five major Irrigation Regions in the Basin; the Shepparton, Kerang, Murrumbidgee, Deniliquin and Wakool Regions. Their gross area is 1.75 million ha.

On a percentage area basis, pasture is the dominant irrigated culture in the Victorian Regions, but the relatively small area of horticulture in the Shepparton Region has played a major part in its economy. For the Deniliquin and Wakool Regions the main enterprises are based on irrigated pastures, with rice growing also significant. The Murrumbidgee Region has an area of horticulture similar to Shepparton's, with the remainder of the irrigated area evenly divided between pasture and rice.

Irrigation has enabled the Regions to be settled more intensively than with dryland farming. For example, at the time of the 1971 Census, the Shepparton Region supported 70,000 people. Comparison with nearby 'dry' municipalities suggests that without irrigation this figure would be 30,000.

Works have been undertaken to cope with water table problems which have arisen in the Murrumbidgee Region, and disposal is believed to affect only slightly the Murrumbidgee River (and hence River Murray) quality. Discussion therefore centres around the other four Regions.

An estimate of the increase in the area of high water tables with time in the 'Do-Nothing' case, produced by the Consultants, is shown in Fig. 6. Although the estimate was based on incomplete data, and would probably be revised if the exercise were repeated using updated information, it is useful for indicating likely trends.

The Consultants' estimate was that for 1970 there would be 260,000 ha with high water tables, with 80% of this area in the Kerang Region. There has been evidence of high water tables and salinisation in this Region since early this century. A consequence of the salinisation is the high salinity of runoff from surface drains, many of which were constructed in the 1930s.

According to the Consultants, the total area of high water tables will expand rapidly from 1975 onwards, with the Shepparton and Deniliquin Regions contributing the biggest increases.

In May 1975 the Victorian Water Commission (SR&WSC (Vic.) 1975) advanced a plan for the protection of the more intensively irrigated parts of the Shepparton Region from water logging and salinisation. This plan has since been developed in more detail. As the Shepparton situation is believed to be indicative of that which is developing, or will develop, in much of the area of the other Regions, it will be described at some length here.

A program for protection of horticultural areas (about 6,600 ha) by groundwater pumping is half completed, and the concern now is for 125,000 ha of intensively irrigated pasture land which either has a high water table, or is soon expected to develop one. The immediate effect of a high water table developing beneath an intensively irrigated pasture property is a productivity drop of five percent. Ultimately, this will become 25% as salinisation takes effect. It has been calculated that if this situation is allowed to develop the decline in productivity of the 125,000 ha will result in the Regional population being 5,550 people less than would be the case with no high water table. The proposal put forward involves the lowering of the water tables by 450 pumped tubewells in the pasture areas, in addition to the 150 now being installed in horticultural areas. Because the salinity of the extracted groundwater is comparatively low, it would be possible to re-use 50% of it by dilution through the supply channel system. The proposal is to outfall the remainder to the River Murray where the increased salinities should be acceptable down to the Loddon River junction (the average increase would be 75 EC units). From there on normal rises in Murray salinity make it desirable to offset the effect, and it is proposed that this be achieved by increasing the diversion of Barr Creek to 60% of its average annual flow, with evaporative disposal in Lake Tyrrell.

New South Wales has a proposal for the lowering of a highly saline groundwater mound which occurs under 40,000 ha in the Wakool Region. It is proposed to dispose of the extracted groundwater by evaporation, with harvesting of the sodium chloride and injection of the bitterns (1% of the original volume) into a deep aquifer.

Both New South Wales and South Australia have objected to the Victorian plans for the Shepparton Region as outlined above, the principal concern being that the Lake Tyrrell Scheme is

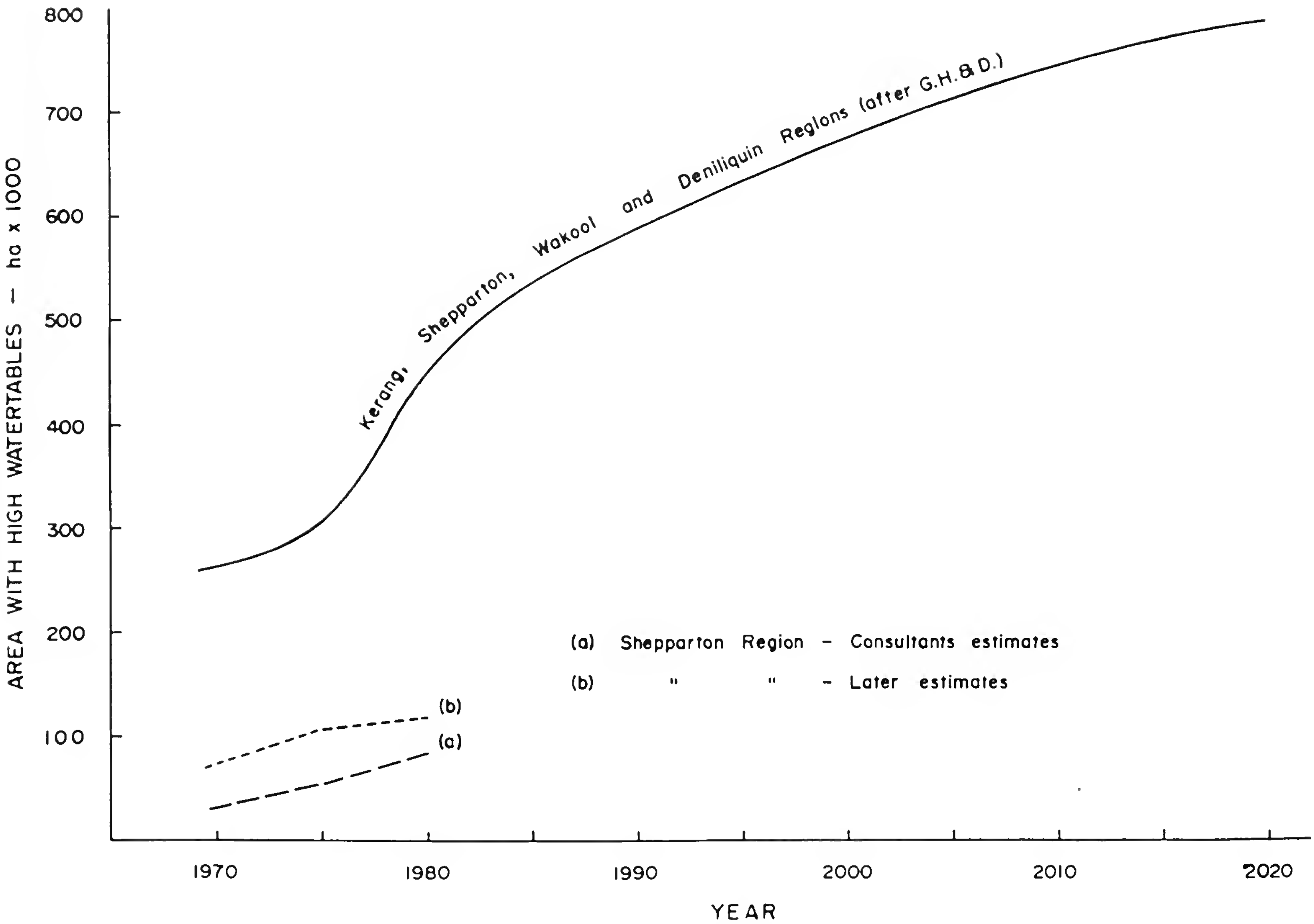

FIG. 6 — Predicted Increase in High Water Tables — Upper States.

proposed to be of a compensatory nature only. South Australia made the following points (E.W.S.D. (S.A.) 1976):

(a) River salinities already experienced can be higher than desirable limits,

(b) there is an apparent rising trend in salinity,

(c) there is a limit to the amount of salt diversion away from the River Murray which can be economically undertaken in South Australia, and,

(d) under these circumstances the acceptability of the Victorian proposal would depend upon Victoria's acceptance of the need for operation of the scheme to provide at all times acceptable salinities to South Australia, and demonstration by mathematical modelling that such operation is feasible.

The three States, through the River Murray Commission, are now moving towards a joint examination of their salinity problems. This is expected to include the development of a 'package' proposal of salinity control schemes, and possibly river regulation procedures, which will cope with the salinity problems of all parties. A ranking of the items in the package into priorities for implementation would also be part of the study.

POSSIBLE JOINT STUDY

Users of water from the downstream reaches of the river may be regarded as being subject to a 'squeeze', represented by the apparent narrowing gap between the desirable salinity limit and average levels already experienced. This squeeze is seen to be due largely to irrigation activities in all three States, which have had the effect of reducing flows in all except drought years, and increasing salt load inputs.

In the author's opinion several questions are pertinent. Firstly, what salt load, if intercepted and diverted away from the river, would hold the squeeze at an acceptable pressure? Secondly, how does this compare with the salt load which it is practicable to divert away from the river? Thirdly, is there also scope for offsetting salinity increases which may come from future drainage works in irrigation areas? Fourthly, if it is not practicable to divert sufficient salt load for both purposes, are

there other feasible measures which, together with salt load diversion, would have the desired effect? These measures could involve changes in the crops grown in irrigation areas supplied from the river, or changes in irrigation techniques. Fifthly, if this is not the case, which areas will have to accept less than desirable conditions of supply or drainage?

An obvious prerequisite for a study of salinity problems is a sequence of River Murray flows for use in simulation of the system behaviour. This sequence must represent expected future conditions of diversion and impoundment. Also, agreement will have to be reached on the degree of damage and economic loss which would be caused at various levels of river salinity.

Perhaps the most important point to resolve before commencing the study proper is the amount of salinity increase to be expected in future in the 'Do-Nothing' case. Factors which could have influenced the rate of rise in the past are:

(a) The opening up of new irrigation areas, with drainage disposal back to the river, either directly or indirectly. An example of indirect disposal is drainage to evaporation basins, close to the river, which leak or overflow.

(b) The intensification of irrigation in salinised areas, which has the effect of increasing saline drainage runoff. For example, between the early 1940s and the present, the amount of water applied to the Barr Creek catchment has increased by about 30%. Also, in both (a) and (b), diversion of water for irrigation would tend to increase river salinities by reducing river flow.

(c) The extension of surface or sub-surface drainage in areas with salinity problems. In some areas pumps extracting highly saline groundwater were allowed to discharge to surface drains.

(d) The salinisation of land already surface drained.

(e) The development of groundwater mounds beneath irrigated areas causing direct accessions by seepage.

(f) A general rise in water table levels in some areas traversed by the Murray and its tributaries, resulting from activities such as land clearing.

(g) The apparent increase in salinity of runoff due to deterioration of some catchments.

Clearly, the contributions of each of these factors will have to be quantified. Those factors which are likely to continue to cause rises will need to be identified, and taken into account in the formulation of a joint strategy.

ACKNOWLEDGMENT

The author wishes to thank the State Rivers and Water Supply Commission for permission to publish this paper. The views expressed are the author's, and not necessarily those of the Commission.

Appendix A

THE PROVISIONS OF THE RIVER MURRAY WATERS AGREEMENT IN RELATION TO FLOWS TO SOUTH AUSTRALIA

The River Murray Waters Agreement specifies that a quantity of 1.55 million megalitres is to be allowed to pass into South Australia each year, in specified monthly amounts, monthly excesses not counting as part of the annual entitlement.

The Agreement requires the River Murray Commission to maintain certain reserves (1.23 million megalitres at present) in Hume Reservoir and Lake Victoria, for use in dry years. If the storages fall below the reserve quantity, the Commission is required to declare a 'period of restriction'. Also, in a drought year, the Commission may make such a declaration even if the storages exceed the reserve. During the period of restriction, the Commission is obliged to assess the quantity of water likely to be available. In assessing the quantity, deductions have to be made for losses and for the special purpose of providing for dilution, lockages and evaporation in the South Australian reach of the Murray. The available water is then divided between N.S.W., Victoria and South Australia in the ratio 5:5:3.

In the post-Dartmouth situation, the South Australian entitlements will be as follows:

(a) the annual entitlement will be increased from 1.55 million megalitres to 1.85 million megalitres. Also, the specified monthly entitlements will be altered, as shown in Table A-1;

(b) in periods of restriction, the available water will be shared equally between the three States.

Table A-1
South Australian Monthly Entitlements

	Monthly Entitlement (Ml/d)[1]	
Month	*Pre-Dartmouth*	*Post-Dartmouth*
July	1,900	3,400
August	3,700	3,900
September	4,700	4,400
October	4,500	5,400
November	5,500	6,100
December	5,300	7,100
January	5,300	7,100
February	5,900	6,600
March	4,500	5,800
April	3,900	4,600
May	3,700	3,200
June	1,900	3,300

(1) The Agreement specifies the entitlement in terms of monthly flow, but Ml/d is used here for consistency with the rest of the paper.

APPENDIX B

DETAILS OF SALINITY CONTROL WORKS

LAKE VICTORIA/BRILKA CREEK (STAGE I)

Lake Victoria, an offstream storage near the South Australian border, has raised groundwater levels adjacent to a number of side channels of the River Murray. One of these is Brilka Creek, which intercepts some of the groundwater, and in the past has added it to the River Murray. The Stage I works prevent Brilka Creek flow to the Murray, and inflows to the Creek evaporate from its surface, unless deliberately released. Stage II (not yet constructed) would involve the damming of one other side channel, and pumping of intercepted groundwater to an inland evaporation basin.

BARR CREEK/LAKE TUTCHEWOP (VIC.)

In this scheme, about 15% of the average annual flow of Barr Creek is diverted to the nearby Lake Tutchewop and three smaller basins for evaporation. However, at certain times much higher proportions than 15% are diverted, with consequent large reductions in river salinity at points downriver.

LAKE HAWTHORN (VIC.)

Lake Hawthorn receives saline drainage from irrigated land in the Mildura-Merbein area. The Lake Hawthorn Scheme consists of works to take water from the Lake to inland evaporating basins at times when outfall to the Murray River is undesirable.

CURLWAA I.A. (N.S.W.)

The Curlwaa I.A. occupies 4,200 ha near the town of Wentworth. The scheme consists of four pumped tubewells which control the level of a groundwater mound which had built up. This scheme serves the dual purpose of protecting land from waterlogging and salinisation, and preventing salt accessions to the River Murray.

RENMARK RESERVOIR (S.A.)

Renmark Reservoir (or Salt Creek) is a side channel of the Murray which once formed part of the irrigation supply system at Renmark. It is no longer included in the supply system, and acts as a collector of saline groundwater. The Stage I scheme dams off Salt Creek, so preventing salt accessions to the river, unless intentional releases are made. Stage II, an interim measure which could be constructed pending permanent evaporative disposal facilities becoming available (Stage III), would comprise pumps, and a pipeline connection to the Dishers Creek evaporation basin. Seepage from this basin would reduce the benefit of any pumping of saline water from Salt Creek.

MILDURA-MERBEIN GROUNDWATER INTERCEPTION (VIC. & N.S.W.)

Irrigation adjacent to this reach of the Murray has created groundwater mounds which cause salt accessions. Pumped tubewells are proposed along both banks of the river to intercept the seepage. Disposal will be by evaporation in inland basins.

NOORA BASIN (S.A.)

The Noora Basin is an inland depression which could be used for evaporation of subsurface drainage piped from irrigated land in the vicinity of Berri, Barmera and Cobdogla. Currently, disposal is to basins close to the river.

LAKE TYRRELL SCHEME (VIC.)

The Lake Tyrrell Scheme would be an extension of the present Barr Creek/Lake Tutchewop Scheme, in which a 90 km channel and pipeline between Lakes Tutchewop and Tyrrell, together with increased capacity pumps on Barr Creek, would enable a much greater proportion of Barr Creek flow to be diverted. If pumping were carried out only at times when river salinities were of concern to users, about 100,000 tonne/year more than the present amount would be diverted to evaporation. The Lake Tyrrell Scheme is part of a proposed 'package' put forward by the Victorian Water Commission, and would have the function of offsetting the effect of proposed outfalling of groundwater from the Shepparton Region.

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12

HYDROLOGIC CHANGE IN THE LODDON BASIN: THE INFLUENCE OF GROUNDWATER DYNAMICS ON SURFACE PROCESSES

By P. G. MACUMBER*

ABSTRACT: The late Tertiary Loddon Valley 'deep leads' drainage system passed from the highlands across the Loddon Plains to flow into a Murravian Sea in the far north of the State near the present day Murray River. This ancient drainage channel, now buried sixty metres below the plains, forms the major groundwater path for sub-surface flow from the Central Victorian Highlands. Within the highlands the pressure levels of the Calivil Formation aquifer formed of the deep lead gravels are well below surface level, but become artesian (flowing) in the mid-Loddon Plains. Monitoring of the potentiometric surface over a seven year period indicates that water loss to the surface contributed to present day high salt levels on the Loddon Plain. Rapid rises in pressure levels observed during the two year wet period 1973/74 indicate a high degree of sensitivity of the deep groundwater regime to minor climatic fluctuations. It provides an important clue to the nature of groundwater discharge elsewhere on the plains, and during the well documented phases of high stream flow of late Quaternary times.

INTRODUCTION

The Loddon River drainage basin covers an area of about 15,500 km^2 in northwestern Victoria stretching from the Great Dividing Range to the Murray River. The Loddon is the most westerly of the north flowing streams tributary to the Murray River: for a little less than half its entire length the Murray and its tributaries flow along a valley tract within the highlands. It emerges from the highland front near Bridgewater and thereafter flows as a distributary system across the Loddon Plains, a southwestern part of the more extensive Riverine Plains.

Within the highlands the Loddon Valley is infilled with a thick alluvial sequence. The coarse 'wash', gravels, pebbles and boulders at the base of the alluvium, proved to be one of the richest areas of gold production during the late 19th and early 20th centuries. Geologists of the time established the presence of a late Tertiary 'deep lead' drainage system, ancestor to the present system, but now buried to a depth of more than 100 m. From the outset water within the coarse sediments of the alluvial infill proved a major obstacle to mining, as these gravels provided the major flow paths for groundwater moving plainwards from the Divide. Downstream, beyond the highland front, there was no mining and the course of the valley was lost under the alluvium of the Loddon Plains.

During the drought of 1967-1968, the urgent need to provide good quality water in the northern Victorian shires stimulated investigation of the groundwater potential of the deep lead systems beyond the highlands.

The drilling program commenced in 1968 showed that the Tertiary valley continued across the Loddon Plains as a trench incised into a pre-existing peneplain termed the Mologa Surface. This peneplain is now buried to an average depth of about 70 m, with the ancient river valley incised into it a further 30 m. The average width of the trench is about 5 km.

In the far north of the Loddon Plains, the deep lead system joined a westerly flowing Murray Valley system immediately prior to entering the late Tertiary Murravian Sea (see Fig. 1).

CLIMATE

Rainfall is closely related to topography in the Loddon Drainage Basin. The heaviest rainfall averaging about 1060 mm occurs on the Divide near Lyonville, at the junction of the headwaters of the Lerderderg, Coliban and Loddon Rivers; it decreases to the west to average about 710 mm on

* Geological Survey, Victorian Department of Minerals & Energy, 109 Russell Street, Melbourne, Victoria 3000.

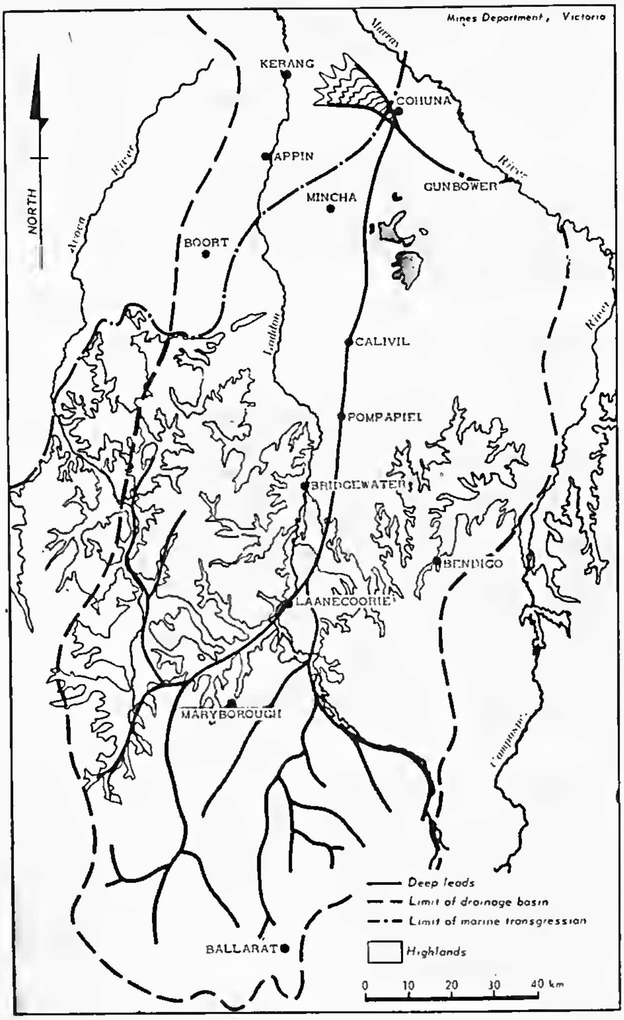

FIG. 1 — Loddon drainage basin — late Tertiary.

the basaltic plateau west of Ballarat. Northwards across the basin there is a steady decline in rainfall such that the Loddon Plains lying roughly between the 350 mm and 450 mm isohyet have a semi-arid climate.

There is a marked incidence of winter rainfall especially in the catchment areas, and at Lyonville the wettest month of June has three times the rainfall of the driest, February. The drier summer period coincides with the time of highest temperature.

Like the isohyets, the isotherms closely relate to the physiography. February is the warmest month, with a mean average value ranging from 18.3°C at Ballarat in the south to 23°C at Kerang in the north. The coolest month is July with mean monthly temperatures ranging from 6.7°C at Ballarat to 8.9°C at Kerang.

GEOLOGY AND STRATIGRAPHY

MOLOGA SURFACE

In late Tertiary times, an extensive plain (the Mologa Surface) covered almost the entire area now represented by the Loddon Plains. This was later covered by fluvio-lacustrine and marine deposits; it is now met only in bores at depths from about 60-75 m below the present surface.

In the western parts of the Loddon Plain the Mologa Surface is formed on lower-middle Tertiary carbonaceous Renmark Beds, while in the eastern and southern areas it is developed on deeply weathered Palaeozoic sediments. Extensions of the surface have been traced eastwards of the Terrick Terrick Range and under the western Campaspe Plain. It is considered to be middle Miocene in age.

LODDON VALLEY LEAD

The ancient effluents tributary to the Loddon system commenced near Ballarat, Bullarook, Spring Hill, Creswick, and Lake Learmonth (Hunter 1907). After the confluence of the Bullarook-Mount Prospect Lead and the main Ascot-Clunes Lead in the Parish of Smeaton, the Loddon Valley lead gains substance, and it continues as the trunk Berry-Moolort-Loddon Lead passing northwards through the parishes of Glengower, Redborough, Moolort, Baringhup, Neereman and Laanecoorie. The course passes into the Parish of Woodstock which is the most northerly point where, during the gold mining era, drilling was carried out to determine its true position and character.

The confined Loddon Valley gives way to the Loddon Plains near Bridgewater, and here the trunk lead system emerged from the highlands. A cross-section at Woodstock, about 20 km to the south and still within the highlands shows 103 m of sediment overlying Ordovician basement. A generalized section is:

Depth (m)	*Lithology*	*Stratigraphy*
0- 49.4	clay and sands	Shepparton Formatio
49.4- 87.2 87.2-100.9 100.9-103	coarse sand coarse gravel gravel and pebbles	'Deep Lead' Sediment (Calivil Formation)
103 -105.8	slate (Ordovician)	Basement

The infilled channel is about 1.5 km wide and contains 53.6 m of coarse sand, gravel and pebbles.

In the parish of Bridgewater a section shows the system as a 3.2 km wide valley incised 61 m into a

flat Palaeozoic plain, the Mologa Surface, which, as stated, is itself about 60 m below the Loddon Plain. At this point the valley has an asymmetric cross section with an abrupt western boundary and a sloping eastern boundary. Infilling of the valley at Bridgewater shows a similar pattern to that found at Woodstock.

Beyond Bridgewater the buried valley continues northwards through the parishes of Yarraberb, Pompapiel, Calivil, Mologa and Mincha West to join a Murray Valley trunk system in the parish of Gunbower West (Fig. 1). Throughout its length its character is that of a valley incised into a pre-existing peneplain. At Bridgewater and Pompapiel in the south the valley is cut into Palaeozoic sediments but the system then passes onto middle Tertiary carbonaceous sediments. A section at Calivil shows lead gravels occurring from 80-98 m, underlain by 52 m of carbonaceous sands, silts and clays of the Renmark Group. At this point the lead valley is cut 18 m into the Renmark Group which there forms part of the Mologa Surface.

Further north, in the parish of Mologa, the Renmark Group is not present and the valley is again cut in Palaeozoic sediments. At this point the lead sediments are about 15.2 m thick and consist of coarse sands and gravels with minor clay seams. This situation continues into Gunbower West, where a Murray Valley system is met.

Calivil Formation

Beyond Bridgewater the coarse pebbly wash so characteristic of the highland tract rapidly cuts out, to be replaced by gravel and coarse sand. The lithologies persist across the plains. For instance at Calivil, the Mines Department bore (Calivil 2) drilled over the lead has the following lithologies:

Bore Calivil 2

Depth (m)	*Lithology*
0- 51.8	clays with minor shoe-string sands
51.8- 76.8	dense sandy clays
76.4- 95.1	gravels with some minor white clay (Calivil Formation)
95.1-150.3	ligneous sand and clays (Renmark Beds)
150.3	Palaeozoic bedrock

The clean quartz pebbles, gravels and sands so characteristic of the deep leads has been termed the Calivil Formation (Macumber 1973).

Once on the plains there is a gradual thinning of the Calivil Formation from 61 m at Bridgewater to 18 m at Calivil. Beyond Calivil the sequence remains fairly constant, varying from 15-18 m in thickness. The downstream decrease in thickness between Bridgewater and Calivil is seen as the result of a gradually rising marine base level which caused a general upstream movement in the zone of coarse clastic sedimentation (Macumber 1978a). This would also account for the upward fining seen in some sequences.

The gravels and sands are clean throughout the entire length of the system as suggested by their exceptionally high permeabilities measured from Bridgewater in the south to Gunbower in the north (see Table 1). Measurements of the permeablities of the Calivil Formation were carried out at Bridgewater, Calivil, Mincha West and South Cohuna by pump tests using a discharging bore and one or more observation bores. Constant discharge tests were carried out and the results analysed by using the Theis type curves solution for radial flow in an infinite leaky aquifer.

Table 1

Locality	*Transmissivity*
Bridgewater	$5.2 \times 10^3 m^2$/Day
Calivil	$8.9 \times 10^2 m^2$/Day
Gunbower West	$4.3 \times 10^3 m^2$/Day

The hydraulic conductivity at Bridgewater is 85 m/D but falls to 59 m/D at Calivil. Gunbower West is on a Murray Valley system. These values fall within the range given by S. W. Lohman (1967) for coarse gravels, and by Todd (1959) for clean sands, and mixtures of clean sands and gravels.

Although the end of coarse clastic sedimentation is generally sharp, some bores show an upward decrease in grain size of the sequence rather than a sharp change to finer grained sediments, e.g. the Calivil bores, Macorna 2, and Gunbower West 2 bores (Fig. 2). Nevertheless in most instances where this occurs there is still a marked cut-out point for coarse clastic sediments of the Calivil Formation type.

Confining Layers to the Calivil Formation

Between Bridgewater and Pompapiel, the deep trench is totally backfilled by coarse clastic sediments. Overtopping of the trench caused sediment to be deposited on the adjacent peneplain. Having no lateral confinement on this upper surface, the streams fanned out and deposited sediment in an anastomosing distributary pattern.

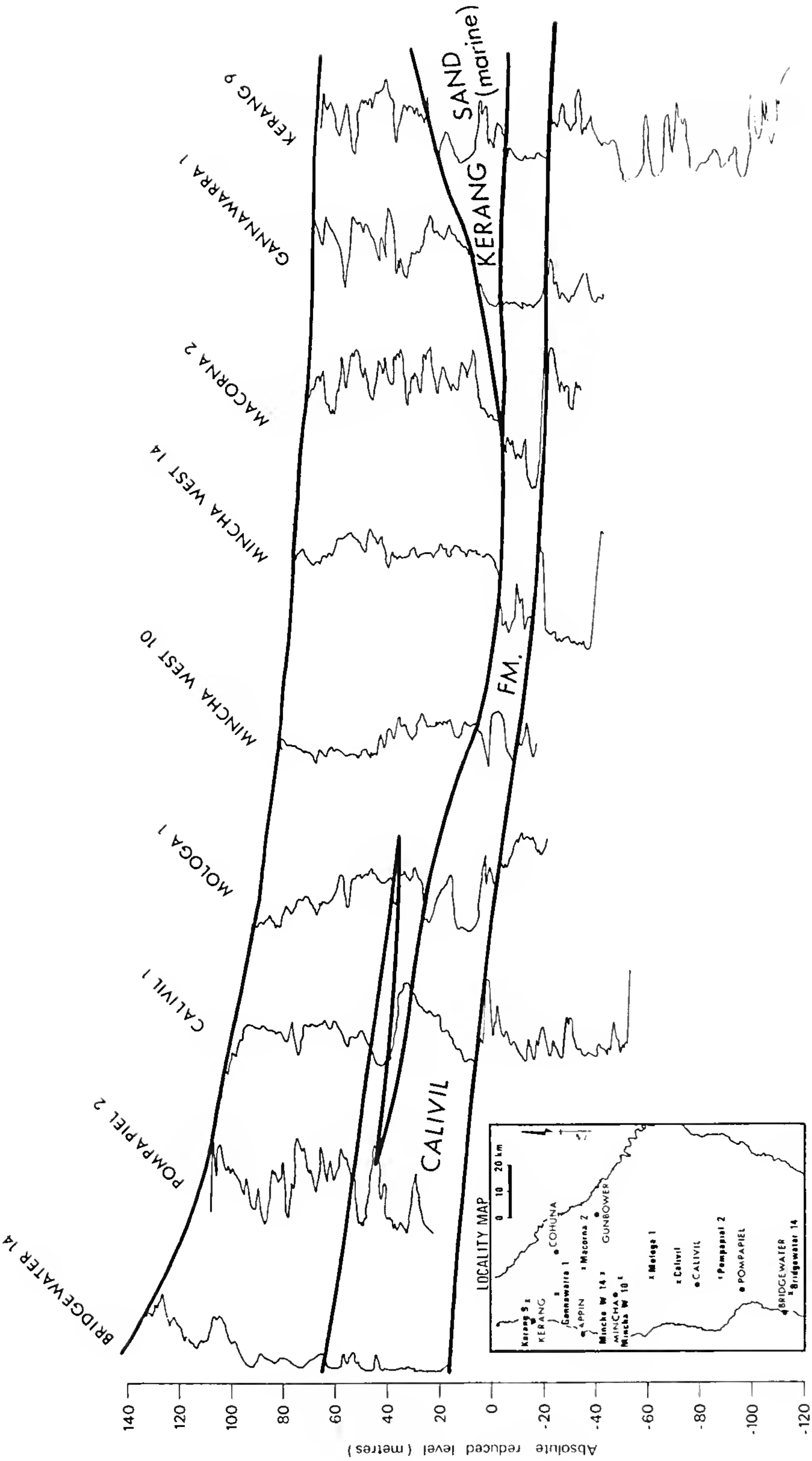

FIG. 2 — Gamma log correlations of the Calivil Formation aquifer down the Loddon Valley.

The channel sediments of these streams are now found over most of the southern plains, as randomly occurring shoe-string sands. Therefore in general bores drilled into the deeper Calivil Formation passing through this zone intersect an overlying major aquifer only when they are drilled over one of the randomly distributed stream channels.

Nevertheless, a sufficient number of bores intersect the aquifers to give rise to a local concept that a 'second stream' exists under the Loddon Plains. The water quality in the upper aquifer is identical with that in the Calivil Formation, with which there is direct aquifer continuity in the southern areas of the plains.

The upper zone of higher permeabilities extends northwards towards Calivil. However, on passing down-basin the top surface of the Calivil Formation falls away with the intervention of a clay wedge which at Calivil is about 15 m thick. Indeed from the central Loddon Plains onwards the deep lead trench is not completely backfilled by coarse sediments: instead the final backfilling is with a dense red and grey mottled clay. This clay forms a virtual valley plug over the Calivil Formation gravels.

With the down-valley increase in thickness and density of the intervening clay wedge there is a concomitant decrease in texture and thickness of the overlying permeable zone, which lenses out after Calivil (Fig. 6). Beyond Calivil the lead gravels are covered by a dense clay aquiclude about 80 m thick.

The effectiveness of the aquiclude therefore differs considerably on passing northwards across the plains. At Bridgewater, a moderately permeable zone extends upwards to within 39 m of the surface. The overlying strata are criss-crossed with shoe-string sands, deposited in a fan-head environment where the Loddon River emerges from the highland front. On passing downstream, however, there is a general decrease in grain size as the stream channels give way to a flood-plain environment. In the central-lower Loddon Plains beyond Calivil a clay lithofacies predominates in the sediments confining the Calivil Formation.

HYDROLOGY

Regional Groundwater Flow

The main catchment areas for the Loddon drainage basin lie on the northern slopes of the east-west trending Western Highlands which make up a western physiographic province of the Great Dividing Range in Victoria. The Great Divide in western Victoria is composed predominantly of Palaeozoic rocks and Tertiary basalts. The latter, in general, form little more than a broad flat low divide — the Ballarat Plateau (Thomas 1956). The outpouring of basalts to form the Ballarat Plateau infilled the existing deeply incised late Tertiary valleys, so modifying the drainage system that it led to a major northwards shift in the Tertiary divide. Much of the intervening area which was formerly part of the Loddon drainage basin now drains southwards along the Leigh River and Mt Emu Creek to the Southern Ocean. The surface drainage basin of the Loddon River is today smaller than its late Tertiary 'deep-lead' equivalent. It is also smaller than the present-day groundwater basin which is substantially the same as it was in Tertiary times.

The effect of water table configuration on regional groundwater flow was demonstrated initially by Toth (1962, 1966). In considering the effect in an area of constant gentle regional slope (as occurs in the case of the Loddon Valley) he concluded that, given a homogeneous medium (which is not the case in the Loddon Valley) this groundwater flow is essentially horizontal, with recharge concentrated at the upstream end of the recharge area and discharge at the downstream end. The 'hinge-line' separating the areas is midpoint, except where a major valley is present, and in this instance the recharge covers most of the upland area and discharge is concentrated in the valley. Freeze (1969) concluded that in a simple two layer system in an area of constant regional slope, the hinge line occurs at the midpoint of the basin. With an increase in permeability ratio, aquifer to aquiclude, the hinge line moves upslope; large permeability ratios are conducive to 'large discharge areas in a simple system where a subsurface highway exists' (Freeze 1969, p. 88).

Clearly the Loddon Valley constitutes a regional drainage system containing a dominant aquifer traversing the basin and acting as a highway for groundwater flow.

From an agricultural viewpoint the position of the recharge-discharge boundary is of prime importance, for it marks the point beyond which water entering the ground cannot overcome the upward potential gradient and will be subject to evapotranspiration in the vicinity of its point of entry.

With flowing artesian conditions present in the basal aquifers, the potential is established for upward moving groundwater to prevent deep percolation of infiltrating surface waters. This is most apparent in areas south of Calivil and north of Mincha West where the aquitard is significantly more permeable than in the central Loddon Plain

(see Gamma log section, Fig. 2). Nevertheless even where the permeability of the aquitard is lower, the presence of flowing artesian conditions will still prevent deep percolation. However with a low permeability aquitard, the rate of upward vertical movement is also correspondingly diminished.

The problems inherent in the large scale flood irrigation of a discharge area are quite obvious. They include waterlogging, increased soil salinities in semi-arid environments resulting from evaporation of irrigation water remaining in the near surface zones, and destruction of vegetation including plants previously evapotranspiring shallow groundwater and thereby suppressing the water table.

Such problems rapidly developed on the Loddon Plains following the introduction of large scale flood irrigation late last century. After only nineteen years, the rising water tables caused severe waterlogging and soil salinization. Many formerly dry lake systems are now either ephemeral or permanent lakes. At present about one third of the district is severely salt affected and virtually the whole of the central and lower Loddon Plains has a water table at less than 2 m (Fig. 3). The immediate cause of salinization is, clearly, the increased water budget following the introduction of irrigation practice. However while the heavy soils of the Kerang Region hinder the deep percolation of infiltrating surface waters, the upward pressure gradients in the groundwater systems prevent any downward percolation. This has led to a rapid rise in water tables, with the irrigation water a significantly greater contributor to the overall water budget than the groundwater system, which acts largely as a hydrostatic barrier to drainage into the deeper strata.

The Loddon Plains beyond Calivil, where the

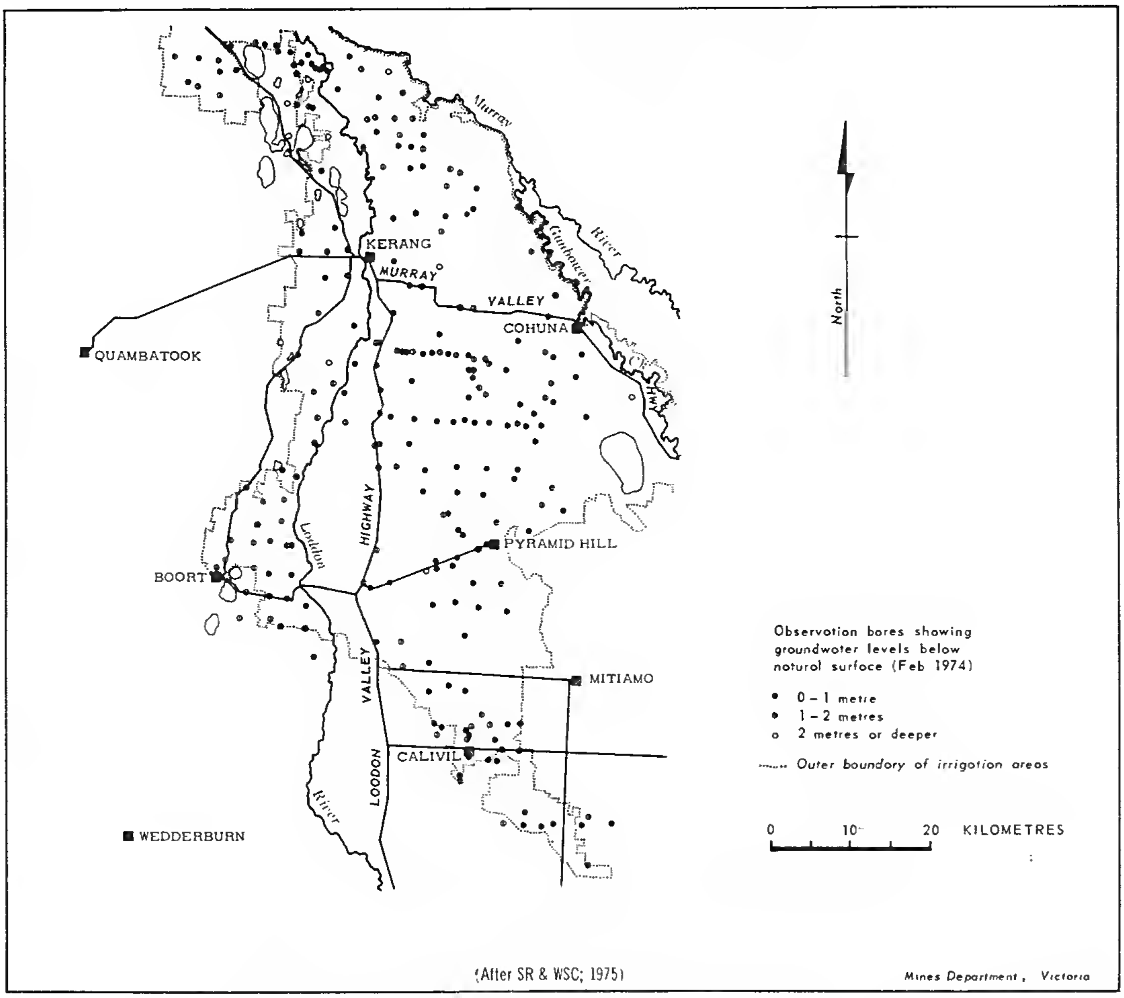

FIG. 3 — Kerang region watertable levels at Feb. 1974.

piezometric surface of the Calivil Formation becomes artesian, shows many of the discharge phenomena. For instance, about one third of the area in the mid-Loddon Plains has a high or very high salinity susceptibility with greater than 0.3% NaCl in the near surface soils. Further north most of the Plains have a very high susceptibility with greater than 0.5% NaCl (Skene 1971). Under pre-settlement conditions regional groundwater discharge took place by evapotranspiration by prior stream woodlands and phreatophytes, and by direct loss to rivers and lakes. The prior stream woodlands (Skene 1971) are best developed on levees of Pleistocene streams, the aquifers of which are in direct hydraulic connection with the more deeply buried regional aquifers. Prior stream woodlands are most common in the southern Loddon Plains, but on passing northwards give way to the treeless plain where phreatophytes were widespread prior to European settlement (Macumber 1978b).

Effluent lakes are scattered over the Loddon Plains, and in certain salinas, e.g. Lake Kelly, salt was once regularly harvested. While lakes like Lake Kelly are fed solely by groundwater, other lakes have both a groundwater and surface water inflow, the latter occurring during phases of high stream flow and sheet flooding. During such times the lakes are flushed of their more saline groundwater component. Typical is Lake Wandella, a permanent saline lake near Kerang, where piezometers show a general upward decrease in aquifer pressures. Pressure levels in underlying Parilla Sand aquifer found at a depth ranging from 20 to 80 m are 1.25 m above that of the lake surface. The Parilla Sand is a marine down-basin continuation of the fluviatile Calivil Formation aquifer (see later).

This general picture is in line with observations of Meyboom (1966), who correlated many of the major areas of soil salinity in southwestern Saskatchewan with discharge areas of regional groundwater flow. However, while upward moving groundwater is a significant contributor to the high salinity of shallow water tables, the author has previously demonstrated that salt additions from various other sources have also contributed to the present high salt status of the Loddon Plain (Macumber 1968).

Piezometric Observations

On its course across the Loddon Plain the deep lead valley is cut into Palaeozoic basement except between the parishes of Pompapiel and Mologa. Here it is incised into lower-middle Tertiary Renmark Beds. However, even where the Calivil Formation does not form the basal aquifer, the relatively low permeability of the underlying Renmark Beds means that for all practical purposes the Calivil Formation may still be regarded as the basal aquifer. Furthermore, since the permeability of the Calivil Formation is orders of magnitude greater than the overlying sediments, its potentiometric surface can be meaningfully mapped (cf. Freeze 1969, p. 4).

The potentiometric surface of the Calivil Formation obtained before 1973 was based on some dozens of bores along the infilled lead valley. Its shape was a parabolic curve, some 24 m below the surface at Laanecoorie but rising to only 12.5 m down at Bridgewater; it was artesian (flowing) for low lying bores at Calivil, beyond which point bores either flow or may be considered as existing in an artesian transition zone (see Fig. 6).

In the transition zone, the potentiometric level of the Calivil Formation is within 2 m of the ground surface. The minor fluctuations in topography in this very flat region are sufficient to determine whether or not a bore will flow. Thus the permeable sandy soils developed on the elevated levees of the prior stream system near Calivil are not greatly affected by shallow saline water tables present under the adjacent plain, and are therefore regarded as superior irrigation areas. Bores on the levees intersecting the Calivil Formation do not flow, whereas bores on the plain are artesian. Indeed, the difference in elevation is sufficient for the development of a first order flow system, with irrigation recharge of the permeable levee soils leading to groundwater discharge via capillarity on the adjacent plains.

Climatic Influence

The 1968 program established a series of observation bores to monitor the fluctuations in the deep groundwater system. Permanent Leopold-Stevens water level recorders were established on bores as they were drilled, and those not so equipped were monitored monthly. Nine observation bores are established over the main deep lead valley between Bridgewater and South Cohuna.

Before 1973 a regular seasonal pattern of minor fluctuations in pressure levels was recorded, with a slight drop over the summer months and a similar rise in winter. The total amplitude of the fluctuation over a four year period was only 0.6 m, peaking in late winter (Fig. 4). During 1973-74 anomalously high rainfalls were experienced in the catchments (Tables 3 & 4) and the plains were subjected to sheet flooding via the distributary

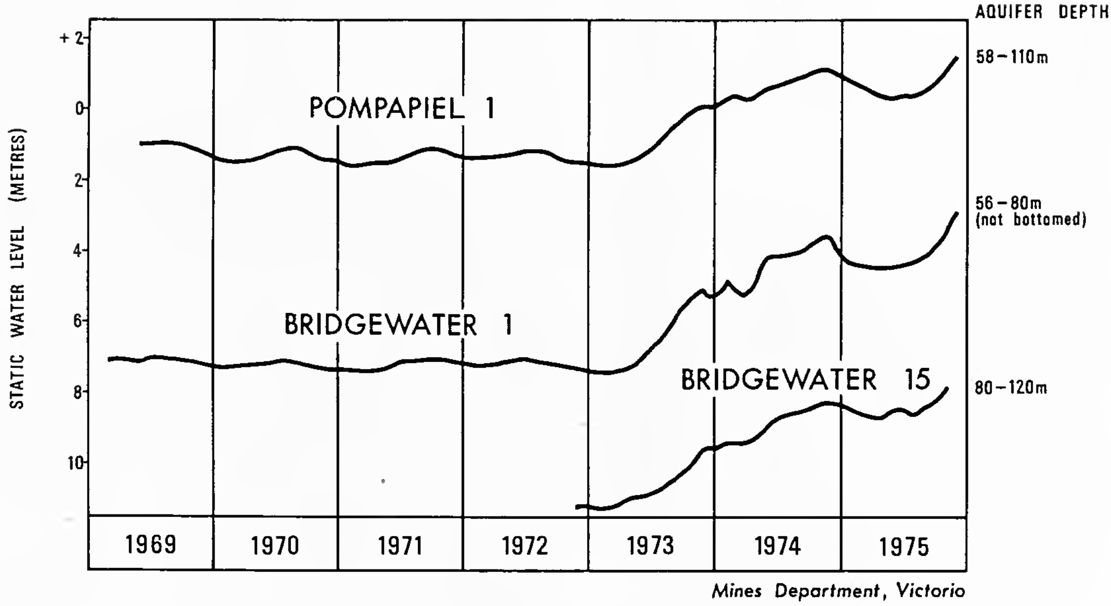

FIG. 4 — Hydrograph of the static water levels — Calivil Formation.

TABLE 2

PRECIPITATION AT SELECTED STATIONS (mm)

Station	*1973*	*Mean*	*% Increase*
Ballarat	958	713	34
Boort	878	389	126
Maryborough	1022	518	97
Bendigo	1017	549	85

systems of the Loddon River and Serpentine Creek, and by Bullock Creek (Fig. 5).

In Autumn 1973, the pressure levels of the Calivil Formation began to rise and by early winter they had surpassed the highest levels reached during the four previous years; they continued to rise throughout the remainder of 1973 and peaked in late spring 1974. The rise was 3.5 m at Bridgewater, 3.7 m at Yarrayne and 2.8 m at Pompapiel (see Fig. 4). As a result of the rising pressures, bores from Pompapiel to Calivil began to flow for the first time since observations were begun, the observation bore at Pompapiel rising to 1.10 m above the natural surface.

The wet period of 1973-74 was followed by an abnormally wet spring in 1975, with further sheet flooding of the plains. Pressure levels again rose, but from a base level well above that of the pre-1973 period. In all bores on the southern plains the previous peaks had been surpassed by mid-October. The Pompapiel No. 1 static level had by November reached a point some 1.5 m above the surface. New levels at Bridgewater No. 1 bore were only 3.7 m below the surface, a rise of 4.5 m over the levels of early 1973.

Since the most southerly artesian bore up to 1973 had been at Calivil, the flowing bore at Pompapiel showed that the point at which the lead system had become artesian had moved upgradient a distance of over 20 km (Fig. 6). In this new position the aquifer is overlain not by the lower permeability aquiclude as at Calivil but by a significantly more permeable aquitard. Indeed at Bridgewater the sediments overlying the Calivil Formation are

TABLE 3

STREAM FLOW IN THE LODDON RIVER AND TRIBUTARIES

Stream	*Discharge 1973 (Ml)*	*Mean Annual Discharge (Ml)*	*Discharge 1956 (Previous Peak flow) (Ml)*
Bet Bet Ct at Norwood	6.8×10^4	1.7×10^3	4.9×10^3
Tullaroop Ck at Clunes	1.2×10^5	6.1×10^4	1.7×10^5
Loddon River at Laanecoorie	1.5×10^6	2.5×10^5	8.1×10^5
Loddon River at Appin	3.0×10^5	1.0×10^5	3.0×10^5

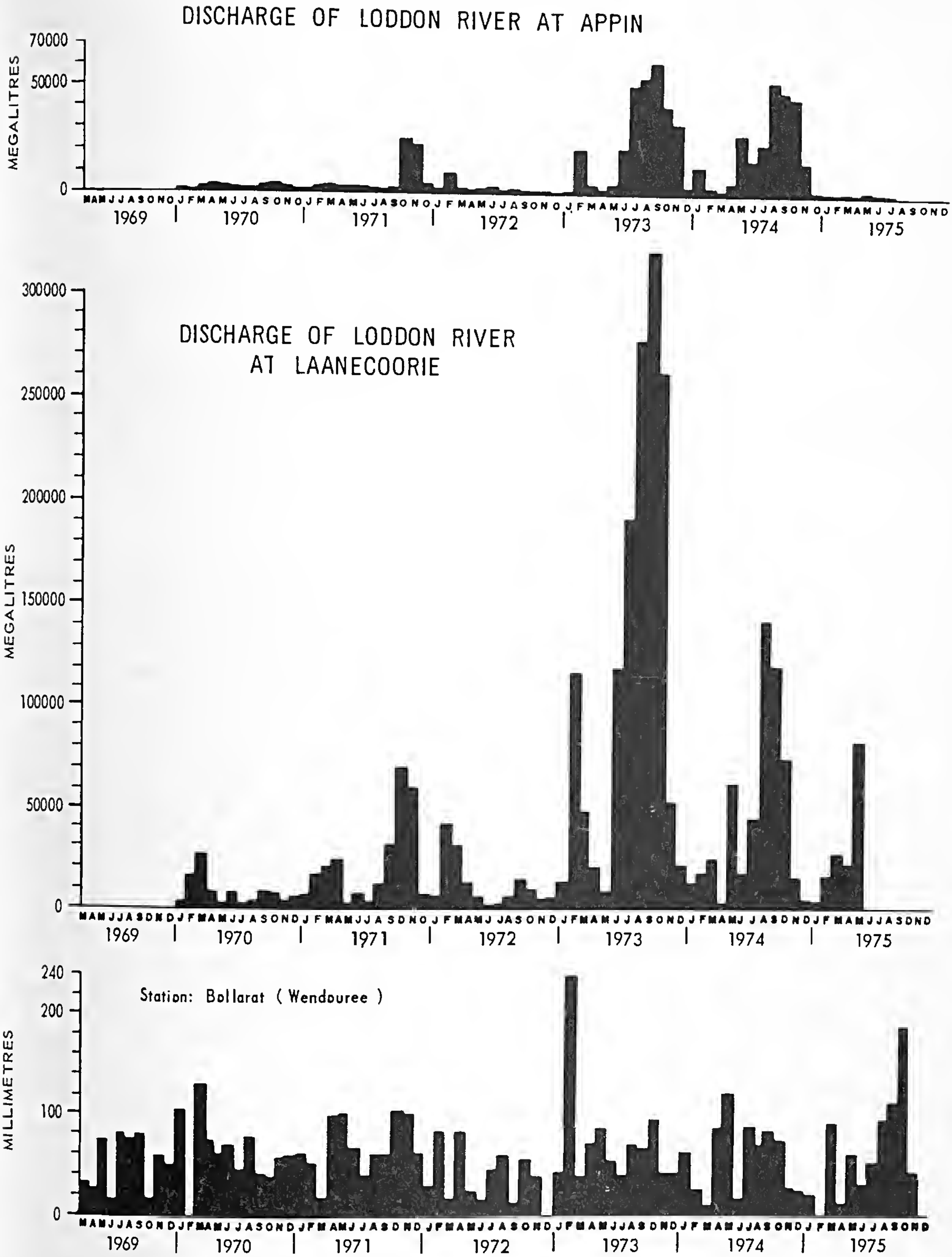

FIG. 5 — Rainfall in the Loddon River catchment, and Loddon River discharges at Laanecoorie and Appin 1969 to 1975.

TABLE 4

EXAMPLES OF LOW SALINITY WATERS IN THE UPPER LODDON PLAINS

Bore No.	*TDS (mg/l)*	*HCO_3+CO_3/ $Cl+SO_4$ (% me/l)*	*Depth (m)*
Yarraberb 15	191	0.7	18.3-24.4
Yarrayne 10002	228	1.03	5.5- 7.6
Yarrayne 10002	368	1.06	29.0
Yarrayne 8	372	0.86	24.1-24.7
Yarraberb 14	475	0.82	24.4
Yarraberb 9	480	1.04	17.7-26.2
Yarraberb 14	595	0.85	25.3

For comparison an average figure for the Calivil Formation aquifer in the Parish of Yarraberb is given.

Bore No.	*TDS*	*HCO_3+CO_3/ $Cl+SO_4$*	*Depth*
Yarraberb 8007 (L. Dickens)	1223	0.35	65.3

moderately permeable and present only nominal vertical hydraulic resistance. The aquifer is seen as being semi-confined to semi-unconfined.

Upstream from Bridgewater the aquifer system is confined by basalt flows; downstream at Calivil it is overlain by clays. Therefore the higher permeabilities of the aquitard between Bridgewater and Calivil provide an escape valve for pressure build up in the Calivil Formation. During phases of high pressure levels as in 1973-75, the basal aquifer becomes artesian within this area with resultant net upflow into the overlying shallow shoe-string sands. The transmission of water along devious pathways of randomly criss-crossing shoe-string sands spreads the area over which groundwater discharge occurs well beyond the lateral limits of the deep lead valley. During the period of peak potentiometric levels in late 1975 situations were found where intermediate aquifers and even some shallow shoe-string sand systems less than 10 m deep became artesian. Direct hydraulic continuity was firmly established between the shallow system, intermediate system and Calivil Formation.

Shallow water tables and evidence of groundwater outcrop appeared in unirrigated areas that had previously been highly productive. Bears Lagoon, one of many local drainage lines, is incised 3 m below the plain, at a point only 0.2 km west of an area of groundwater outcrop in 1975 when pressure levels were at their highest. The lagoon receives groundwater seepage and salt effloresces along its banks. The local observation that the lagoon has on occasions carried water without any apparent surface source is seen as a groundwater discharge phenomenon. In July 1976, at the height of a severe drought, Bears Lagoon was a flowing effluent stream.

The direct distribution of pressure along the shoe-string aquifers influences the ultimate pressure levels of shallow systems in the middle and lower plains. Since the shallow aquifers are prior streams dying out on the plains they have a decreasing carrying capacity because of lower downstream transmissivities and widths. High pressure levels in the deep Calivil Formation must therefore lead to greatly increased rates of water loss from the shallow systems into the overlying clay layers on the middle and lower plains.

MOBILITY OF THE RECHARGE-DISCHARGE BOUNDARY

On the Loddon Plains the pressure level variations in the Calivil Formation are greatest in Bridgewater bore No. 1, in the Parish of Yarrayne (4.4 m over the period March '73 to November '75). These values fall off to the south and north where Bridgewater 14 and Pompapiel 1 have values of 3.3 and 3.1 m respectively. This decline continues northwards with a range of 0.2 m near Pyramid and 0.8 m at South Cohuna. It is noteworthy that the zone of greatest pressure fluctuation lies between Bridgewater and Pompapiel. With a static level some 1.5 m above surface level, the latter areas are clearly the zone of groundwater discharge. However upstream at Bridgewater, the static levels are sufficiently low to suggest that we have crossed the hinge-line out of the discharge zone. South of the hinge, the area comprising the parishes of Yarrayne and Yarraberb is one where two major surface systems, the Loddon River and Bullock Creek, emerge from their highland tracts onto the plains. It is in this area that the Loddon Fan begins (Macumber 1968), and where, in the early maps, Bullock Creek, which is well established further back within the highlands, is shown as dying out and re-appearing further downstream to become the Pyramid Creek.

It is noteworthy that this is the only area on the Loddon Plains where low salinity shallow groundwaters are found, albeit often in juxtaposition to higher salinity waters. Salinities are often well below 1000 mg/litre and reach as low as 200 mg/litre. The chemical character of these waters, in keeping with their low salinity, is unique

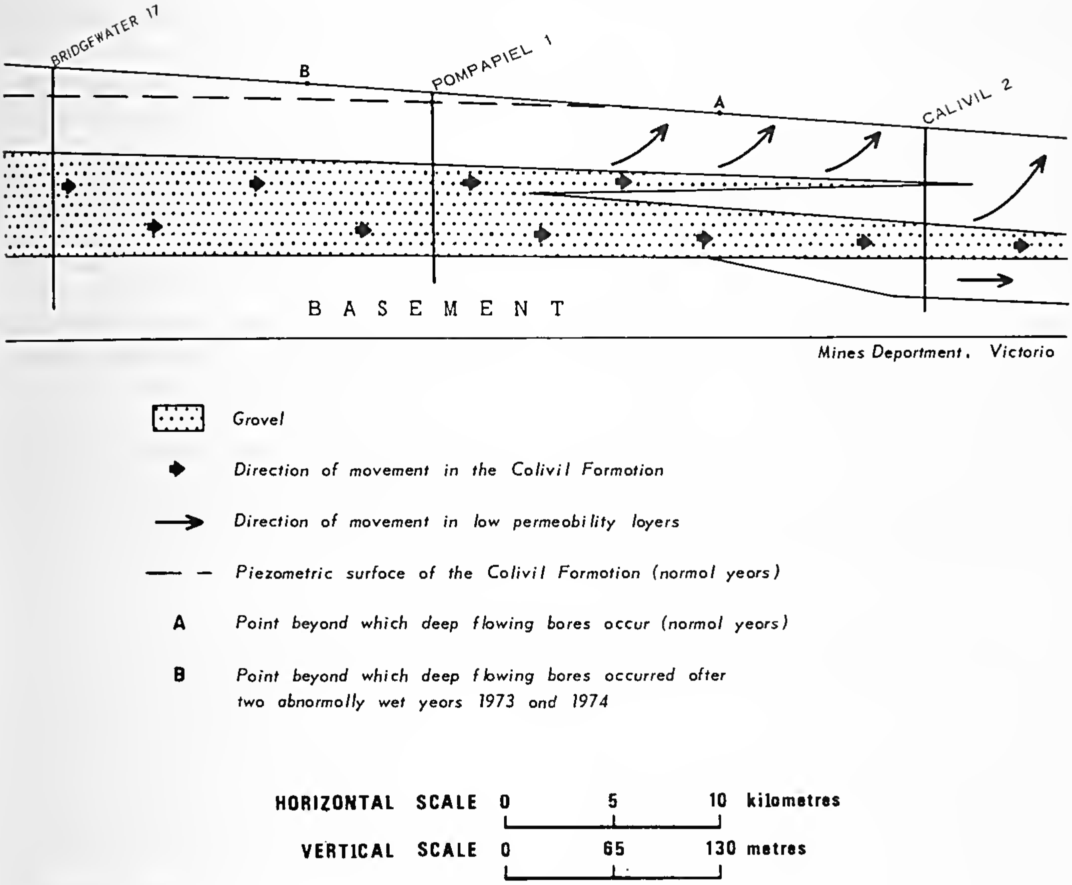

FIG. 6 — Hypothetical flow pattern in the sediments of the south-central Loddon Plain.

to the plains. They have relatively high HCO_3/Cl ratios which in some instances allow them to be categorized in the carbonate-chloride hydrofacies (Table 4). Local recharge is indicated. Therefore the hinge must lie between Yarrayne and Pompapiel. Moreover because of the sensitivity of the potentiometric surface to periodic short term climatic variations, the hinge-line must be considered as very mobile, moving within a zone 20 or more km wide in response to these climatic fluctuations.

REGIONAL EXTENSIONS

Lower Loddon Plains

In the central areas of the Loddon Plains, between Calivil and Macorna, the Calivil Formation is overlain by about 75 m of uniform, moderately dense clay. However after Macorna the Tertiary shore line is crossed; the Calivil Formation is thereafter directly overlain by the marine Parilla Sand. Between Cohuna and Kerang, the Parilla Sand comes to within 18 m of the surface. As on the central and upper Loddon Plains, the standing water level of the Calivil Formation is either at, or very close to, the surface.

Although the overlying units within the Parilla Sand are significantly less permeable than its basal units they would at the most be semi-confining and unlikely to provide much resistance to upward moving groundwater with a positive hydrostatic head. This too is the case for the Quaternary units overlying the Parilla Sand. Between Cohuna and Kerang, the Murray Plains are criss-crossed by a series of shoe-string sands associated with former courses of the ancestral Goulburn River (Macumber 1968, Macumber & Thorne 1975). The situation is therefore similar to that found on the southern Loddon Plains, where shoe-string sands have been shown to provide pathways for upwards moving groundwater. Lawrence (1976) regards this area as being within a groundwater discharge zone.

Riverine Plains to the East

The rapidity and extent to which the pressure levels in the Calivil Formation rose following the

two abnormally wet years of 1973 and 1974 proves an unexpected degree of sensitivity in the deep groundwater regime to climatic fluctuation. Yet waterlogging and salinity problems are not restricted to the Loddon Plains. The rapid rise in aquifer pressures in the Loddon Valley was echoed in part by rises in pressure levels in shallow aquifers, and in the water tables, of the irrigation districts of the Campaspe and Goulburn valleys. This caused large scale losses of fruit trees by waterlogging and salinization (S.R. & W.S.C. 1975). A slow gradual rise in water tables as a result of irrigation had been previously recorded by the State Rivers and Water Supply Commission. However the onset of the wet years 1973 and 1974 led to a sudden dramatic rise in the water tables, and virtually overnight threatened the irrigation districts of the Campaspe and Goulburn valleys. Unlike the situation on the Loddon Plains, the Calivil Formation pressure levels are well below the surface and the hydrological changes are not as yet linked to the regional groundwater flow system. It nevertheless seems that the critical balance that exists between water budget and hydrologic equilibrium on the Loddon Plains is still a fairly acute problem in large areas of the Riverine Plains further east. On a regional scale, a fundamental shift in hydrologic equilibrium is occurring in the regional groundwater flow systems where pressure levels have been rising at a general uniform rate over the past 75 years. This will eventually result in the development of regional groundwater discharge zones on the Campaspe and Goulburn plains (Macumber 1978b).

PALAEOHYDROLOGICAL IMPLICATIONS

It is interesting to speculate on the effects of the late Quaternary periods of very much higher stream discharge than at present, which are well documented on the Riverine Plains (Pels 1966, Bowler 1967, Macumber 1968, Schumm 1968). There is some doubt as to whether the high discharges result from higher precipitation, from lower temperatures, or from both. All would lead to greater recharge of the regional groundwater flow systems.

Given the known response of the aquifer to short term climatic anomalies, the effects of similar events lasting several millennia or longer would have been very profound. Not only would pressure levels have been considerably greater, but more significantly the point at which the piezometric surface intersected the natural surface would have been pushed upstream to beyond Bridgewater, making the entire Loddon Plains an area of groundwater discharge.

Such effects on the hydrogeology of the plains would have been dramatic. Groundwater outcrop would have been a significant feeder to already overloaded surface systems. This is clearly seen in the case of Bears Lagoon which rises in, and drains, the area underlain by the high water tables of 1975 (see Fig 7). Its origin is seen to date back to a time of general high pressure levels and continuous groundwater discharge. This is almost certainly the origin of many of the small streamlet and drainage line traces now found criss-crossing the upper Loddon Plains.

Under extreme conditions of water logging the highly saline shallow water table would have been at the surface in the central lower plains, with the resultant destruction of vegetation. (At present 90% of the shallow groundwater has a salinity of greater

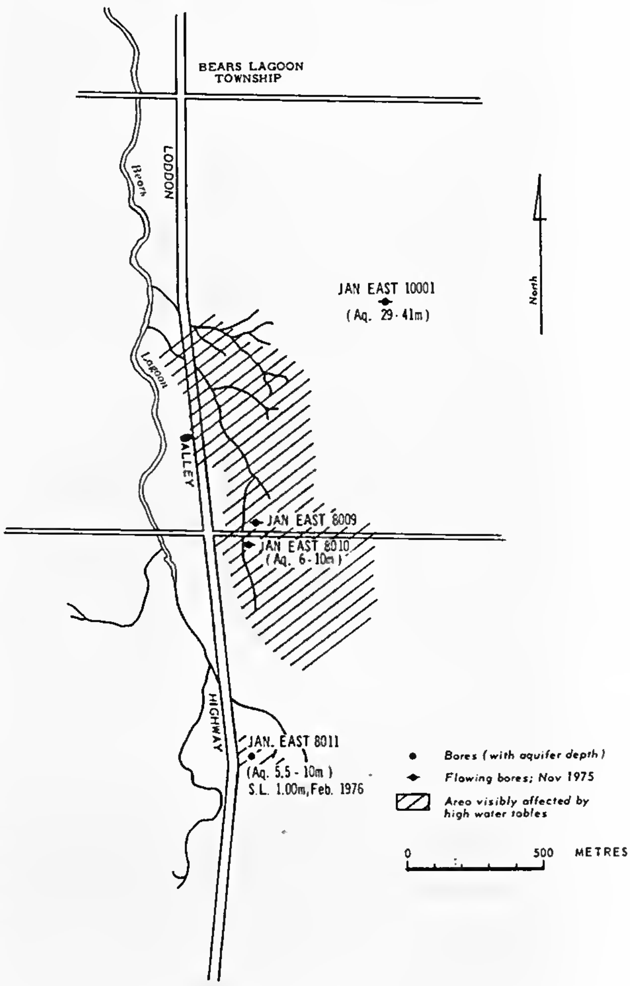

FIG. 7 — Groundwater discharge at Bears Lagoon, November 1975.

than 10,000 mg/litre and 40% is greater than 20,000 mg/l.) The lower-central Loddon Plains would have been a virtual saline swamp, with water loss by evaporation leading to ever-increasing salinity levels. This is in line with the observation that the geochemistry of the shallow saline waters varies little from that of the brackish and fresh waters of the surface systems and deep aquifers.

High water tables were in existence on the Loddon Plains as late as 9,000 years ago as shown by the Kow Swamp study (Macumber 1977). The re-appearance of eucalypts along stream courses and in shallow depressions on the plains at about 8,000 B.P. (Bowler 1968, Macumber 1977) can be interpreted as a response to the decline in regional water tables on the Riverine Plains in early Holocene time.

CONCLUSIONS

(1) The 'deep leads', late Tertiary gravels partially infilling the Loddon Valley, provide the major flow-path for groundwater moving plainwards from the highlands. On the Loddon Plains, hydrostatic forces cause the groundwater to move from the deep aquifer into overlying sediments and to the surface. Much of the Loddon Plain, therefore, lies within a groundwater discharge zone, and this is reflected in the high salt status of the soils and shallow groundwaters.

(2) This study indicates that on the Loddon Plain there is a ready interchange between the groundwater and surface water systems, both of which make up two aspects of a single integrated down-basin flow system.

(3) The high sensitivity of the groundwater system to a small increase in water budget indicates a delicately balanced hydrologic regime. For any full comprehension of the dynamics of the regime consideration must be given not only to the water budget, but also to basin geology and morphology. It demonstrates the need for management and research studies that integrate surface and groundwater hydrology.

(4) A model is provided for understanding the impending development of regional groundwater discharge conditions in other areas of the Riverine Plain. It thus opens the way for a new understanding of past erosional and depositional episodes controlled either by the emergence of discharge zones or by shifting hinge-line effects.

(5) Given an understanding of the structural and stratigraphic framework of the basin, and the dynamics operating within the flow systems, it is possible to gain an insight into the environmental effects that may have accompanied hydrologic changes of the Quaternary age.

ACKNOWLEDGMENTS

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13

SEDIMENT REGIME OF THE DARLING RIVER

By K. D. WOODYER*

ABSTRACT: The Darling River is predominantly a wash-load stream. Deposition of fine suspended sediment occurs within the channel. Rates of deposition on benches within the channel range from 9 to 64 mm per year. Flocculation of montmorillonitic clays may explain these high rates of deposition in favourable locations where shear forces are low. The channel consists of straight and sinuous reaches. The sinuous reaches reflect the time when the channel meandered freely. Under the present flow regime the deposition of montmorillonitic clays has stabilised the channel in this sinuous form. The straight reaches represent recent channel diversion due to blocking of the channel by sediment deposition and vegetation. Absence of natural levees may reflect the relationship of the sediment peak to the flood peak in wash-load streams, and the calibre of wash-load sediment.

INTRODUCTION

The sediment and flow regimes of a river are major determinants of channel form and stability. This paper examines available data relevant to the sediment regime of the Darling River and its expression in channel form and stability.

The Darling River catchment is second only to the Murray River catchment in size, covering an area of 650,000 km^2 in New South Wales and Queensland (Fig. 1). The eastern tributaries originate in the northern tablelands of N.S.W. at elevations up to 1,600 m and in the Darling Downs Region in southeast Queensland. The average annual run-off varies from 30 mm for the Gwydir River to 9.5 mm for the Moonie River. The northern tributaries rise on or near the Great Dividing Range in south-central Queensland. Here the average annual run-off varies from 6.0 mm for the Warrego River to 3.7 mm for the Paroo River. The long-term average annual discharge of the Darling at Menindee is 102 m^{3}s^{-1}representing an average annual run-off of 5.6 mm. The run-off has two main peaks. In summer, rainfalls associated with wandering tropical cyclones in the north of the catchment increase run-off and flooding. In winter, discharge may increase due to rainfall associated with upper-atmospheric convergences.

Large amounts of montmorillonitic clays are derived from basalt and labile sediments in the upper catchment. These cohesive clays play an important role in channel morphology and in sedimentation within the channel and on the flood-plain. Downstream of Goondiwindi the stream traverses flat, low-gradient plains formed primarily of very fine-grained cohesive sediments. The channel gradient decreases progressively to Walgett (some 2,500 km from the Southern Ocean) and then remains fairly constant at about 5 x 10 $^{-5}$.

Large numbers of distributaries, anabranches and palaeochannels divert flow from the main channel during floods. Flood peaks are slowed by storage effects due to this system of channels and general overbank storage. The travel time for flood peaks from Walgett to Wentworth ranges from 60 to 120 days. Normally floods rise very slowly and may last for up to four months. The river has ceased to flow 48 times at Menindee since 1881 for periods of up to 362 days.

METHODS OF INVESTIGATION

Bank and bed sediments were sampled to a depth of 5-7 cm on cross-sections near the gauging stations indicated in Table 1 (for locations see Fig. 1). At the time of sampling the river had ceased to flow. Fourteen sediment samples — four from each bank and six from the bed — were collected at approximately equal distances along the channel perimeter. The samples from each bank and the bed were bulked and subsampled. The percentage of sediment finer than 72 μm and organic matter in these sub-samples was determined. The channel silt-clay percentage was calculated using the weighting method of Schumm (1960).

* Division of Land Use Research, CSIRO, P.O. Box 1666, Canberra City, A.C.T. 2601.

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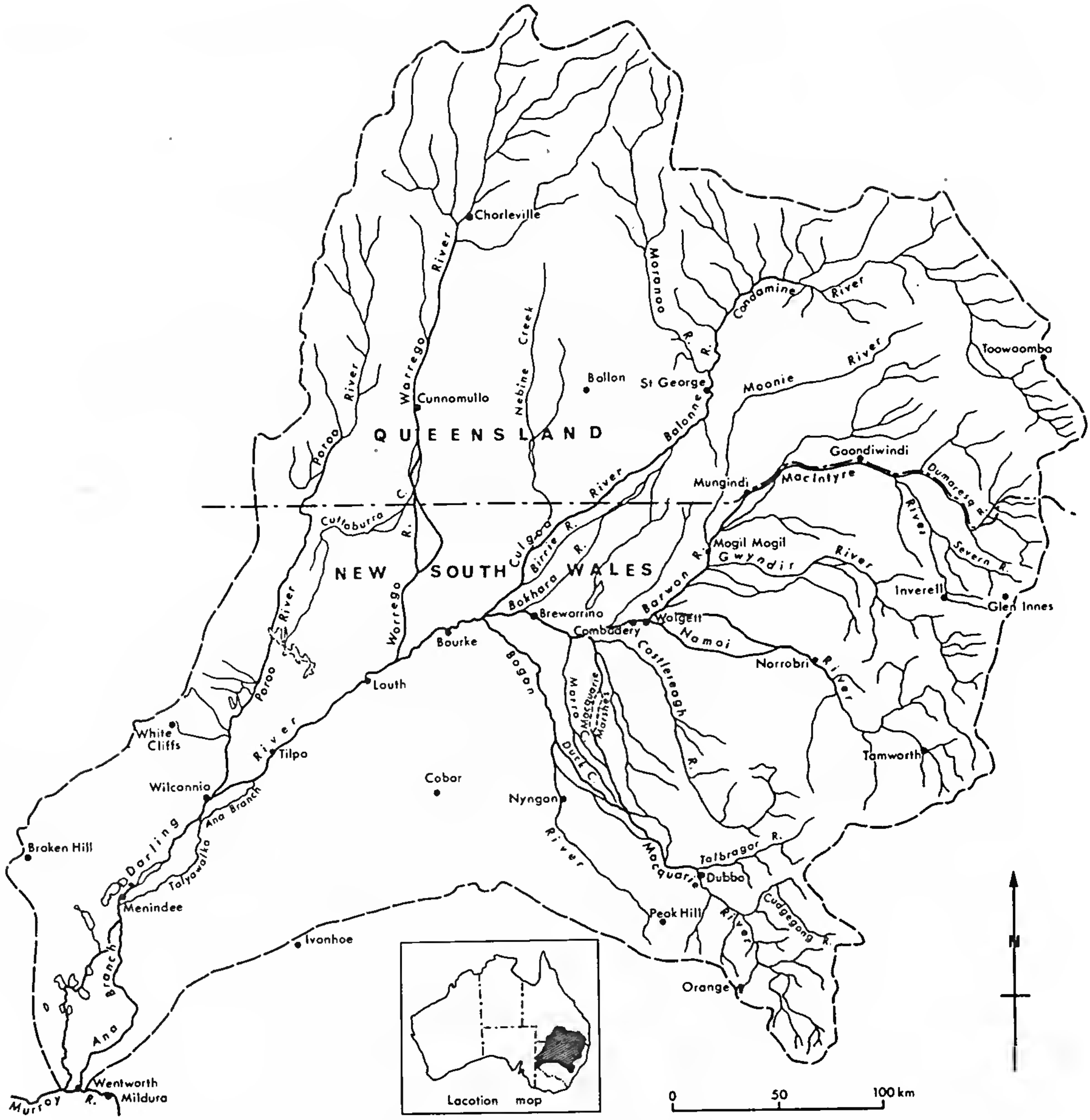

FIG. 1. — The Darling River catchment and location of the gaugings sites referred to in the text.

The channel cross-sections at these sampling sites were surveyed. The width of the channel was measured from the edge of the lower bank to the opposite bank. The depth of the channel was taken from this lower bank to the deepest part of the channel.

Sinuosity is the ratio of channel length to valley length. Sinuosities were determined between the gauging stations in Table 1 using maps at a scale of 1:250,000. The spacing of the sites varies from 102 to 280 km. By using these long reaches, local variations in sinuosities were averaged out. Sinuosities determined in this way are conservative when compared with values obtained by Schumm (1968) for the Murrumbidgee using 8-km reaches. For example, between Walgett and Brewarrina the sinuosity for the 280-km reach is 2.2 (Table 1). This compares with a sinuosity of 2.3 for a 30-km reach downstream from Walgett.

Measurements of rates of deposition of sediment on benches (Woodyer 1968), within the channel, were made using 8.5 mm diameter steel pegs about 15 cm long as surface markers. These were driven flush with the existing surface level at

equal spacing (61-305 cm). The thickness of sediment deposited on these steel pegs was measured following one or more floods (Table 2). Wooden marker pegs were used to facilitate relocation of the steel pegs.

Water samples containing suspended sediment were collected using a 'U.S. D-49 depth-integrating suspended-sediment sampler' (Guy & Norman 1970). Point integrated samples were collected using a U.S. D-49 sampler modified to permit

TABLE 1
CHANNEL DIMENSIONS, SINUOSITIES AND SILT-CLAY PERCENTAGES

Location	Distance from source (km)	Width (m)	Depth (m)	Width-depth ratio	Sinuosity	Silt-clay (%) Bank	Bed	Channel
Mungindi	557	29.6	4.7	6.3		62.3	4.9	18
					1.9			
Mogil Mogil	659	40.5	5.2	7.6		54.3	11.4	21
					1.8			
Walgett	829	59.4	6.6	9.0		61.7	14.5	24
					2.2			
Brewarrina	1109	72.8	10.1	7.2		81.2	24.1	34
					2.1			
Bourke	1315	94.8	9.6	9.9		75.9	-	-
					1.7			
Louth	1507	85.3	9.7	8.8		72.4	1.0	19
					1.9			
Tilpa	1668	92.7	11.3	8.2		81.1	15.3	27

TABLE 2
RATES OF DEPOSITION ON BENCHES

Sampling site*	Period	No. pegs read	Mean thickness per peg (mm)	Mean rate of deposition per year (mm)	Number of inundations	Mean rate of deposition per flood (mm)	Height above thalweg (m)
240 m upstream from station No. 422001 on left bank	May 1971 to Feb. 1974	8	23.7	8.7	3	7.9	6.2
670 m downstream from station No. 422001, on left bank	Dec. 1970 to Feb. 1974	6	85.0	26.2	4	21.3	5.9
Hairpin bend 1.7 km downstream from station No. 422008, on right bank	Oct. 1970 to Feb. 1974	8	57.8	16.9	6	9.6	5.8

*Sampling sites identified by distance from gauging stations (Aust. Water Res. Council 1974).

exclusion of water by air pressure until the required depth for sampling was reached. The concentration of suspended sediment and the particle size distribution were determined using the methods described by Walker *et al.* (1974).

DATA

Channel Dimensions and Sediments

Table 1 gives channel dimensions, width-depth ratios, sinuosities and percentages of silt-clay in banks, bed and the whole channel perimeter, near gauging stations, along the Darling River. These data plot adjacent to equivalent data for the Murrumbidgee River (Schumm 1968, Figs. 24-26) and approximate the regression lines Schumm derived for the Great Plains rivers in the U.S.A. These regression lines are for sinuosities versus width-depth ratios, sinuosities versus channel silt-clay percentages and width-depth ratios versus channel silt-clay percentages.

Fig. 2 compares the values in Table 1 with the values obtained by Schumm (1968) for the

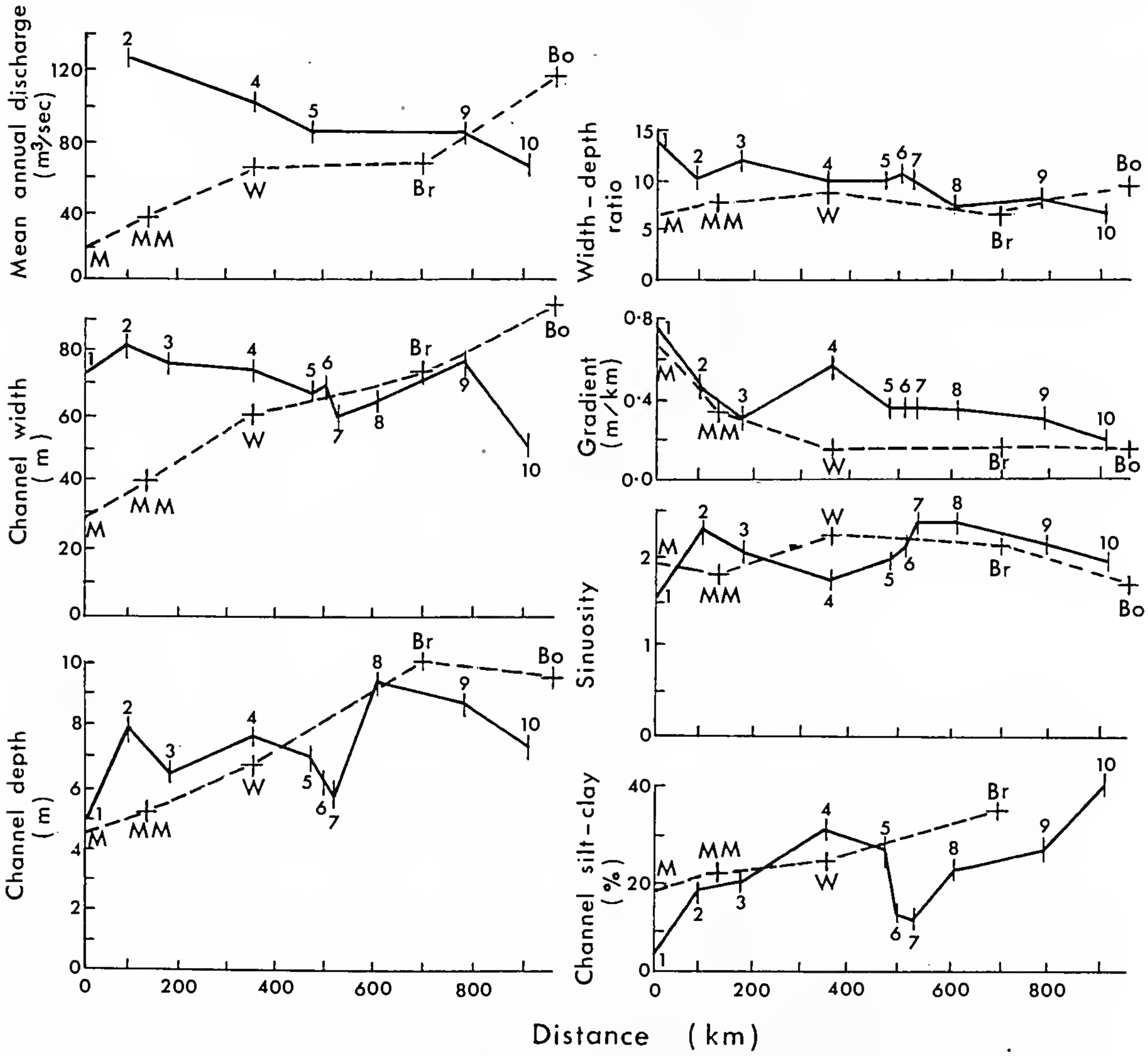

Fig. 2. — Downstream changes in channel character, silt-clay percentage and discharge for Darling and Murrumbidgee (after Schumm 1968) Rivers. Murrumbidgee cross-sections (unbroken line): 1, Wantabadgery; 2, Wagga Wagga; 3, Currawarna; 4, Narranderra; 5, Darlington Point; 6, Yarrada Lagoon; 7, Bringagee; 8, Carrathool; 9, Hay; 10, Maude. Darling cross-sections (broken line): M, Mungindi; MM, Mogil Mogil; W, Walgett; Br, Brewarrina; Bo, Bourke; L, Louth.

Murrumbidgee River. It includes data for the Darling River downstream to Bourke only to give a similar overall channel distance for both rivers. Mean annual discharges are included in Fig. 2 to complete the comparison. The Murrumbidgee differs from the Darling River and most other rivers in that its mean annual discharge decreases downstream. The differences in behaviour of channel width and width-depth ratio downstream in the two rivers reflects the different trends in discharge. Despite this difference there are marked similarities in the general downstream trends for channel depth, gradient, sinuosity and channel silt-clay percentage. The Murrumbidgee channel from about Hay downstream resembles the Darling channel fairly closely.

Pl. 12 shows (above) the channel at the sampling site downstream of Bourke with its steep cohesive banks and sandy bed (see also Woodyer 1968). However, even the sandy bed sediments and particularly the sediments which accumulate by bed-load movement on the points of bends contain montmorillonitic clays, which tend to immobilise them. This, combined with the low energy gradients (1×10^{-4}), results in a very stable channel.

Sediment Transport

Taylor (1976) estimates the total sediment load at Walgett as 420,000 tons per year, of which a maximum of 5% is transported as bed-load. An independent estimate of the percentage of the sediment load which moves as bed-load is 2.5%. This estimate was derived from data presented by Schumm (1968, Fig. 27) and the mean channel silt-clay percentage for all the Darling River sites (Table 1).

At least 95% of the sediment transported by the Darling is fine suspended sediment. Concentrations are generally low: the highest recorded to date is 1,800 p.p.m. Despite the low concentrations the water is turbid. This turbidity is due to the fineness of the suspended sediment. Some 80 suspended-sediment samples were collected near the hairpin bend 1,730 m downstream of Combadery gauging station (station number 422008) (Australian Water Resources Council 1974). Some 80-95% of the suspended sediment (when dispersed for analysis) was finer than 2 μm. These samples were collected during two near bankfull flood-waves in 1969 and 1970. During the 1969 flood a close grid of points was used for sampling in two adjacent cross-sections (Pl. 12, below). The concentration of suspended sediment was uniform throughout these cross-sections. No sediment particles coarser than 37 μm were captured. Numerous laminae containing fine to medium sands occur in the point-bench sediments deposited from suspension (Woodyer *et al.* in press). Either the suspended-sediment sampler failed to capture sand-sized particles or suspension of sand is very intermittent in time and space. This suspension may be related to turbulence associated with sand dunes and bend sharpness (Woodyer *et al.* in press).

An exceptional flood occurred during January 1974 in the Walgett area. Intense local rains caused the most rapid rate of rise of river levels during the 92 years of record (namely 4.34 m in two days). The turbulence associated with this rapid rise brought the sandy bed-material into suspension. When the flood subsided sand was observed in the crevices of the bark of trees to just below maximum flood level. However, apart from these infrequent events, the suspended sediment in the Darling is dominantly wash-load (Einstein *et al.* 1940) with some local suspension and deposition of fine to medium sands derived from the bed-material.

In contrast the tributary streams, at least in the highlands and slopes, carry a great deal more sediment as bed-load. In the steeper more turbulent reaches the suspended-load is dominantly suspended bed-material. As these streams enter the western plains most of the bed-material is dumped and it is mainly the finer suspended load that continues downstream. Examples are the sand deposited by the Castlereagh River north of Coonamble and by the Gwydir River west of Moree. In these reaches and upstream natural levees occur, downstream no levees are present.

The bed-material of the Darling River is highly variable in size distribution over short distances. An example of this is provided by detailed sampling of the bed-material at and near the hairpin bend downstream of Combadery gauging station. Bed-material was collected at 3 m intervals across the entrance to the bend, across the straight reach downstream of this bend and at two sites opposite the point of the bend (Pl. 12, below). In the straight reach the coarsest sediment sample (sample 1, Fig. 3) contained 95% by weight coarser than 62 m and only 2% finer than 2 μm. Samples 2 and 3 (Fig. 3) show the size-distribution range across the channel at the bend entrance. Sample 4 is for bed sediments opposite the point of the bend in the deepest water. This fine sediment is deposited during periods when flow has ceased and water pools in the bend. Apparently it resists subsequent erosion due to the cohesive nature of the clay. Sample 5 is for sediment opposite the point (and adjacent to sample 4) but where the greatest flow velocity occurs at high stage. Sample 5 is similar to

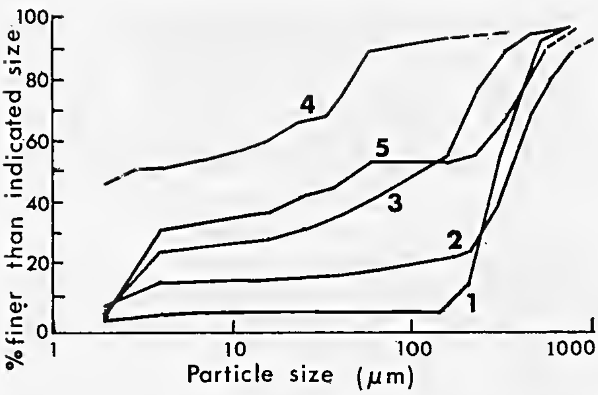

FIG. 3. — Size distribution of sediment samples taken from bed of Darling-Barwon River 1.7 km downstream of Combadery gauging station. Sample 1 from straight reach downstream of hairpin bend and 39.3 m from left bank. Samples 2 and 3 from entrance to hairpin bend 29.3 m and 49.4 m respectively from right bank. Sample 4 from central deep of hairpin bend. Sample 5 adjacent to sample 4 but below filament of maximum velocity (see Pl. 12, below).

sample 4 in respect of the fine fractions, but is comparable with samples 2 and 3 in respect of the coarse fractions. Apparently the higher velocities, where sample 5 was collected, have removed some of the finer fractions. The variability of the bed sediments, particularly adjacent to the banks, is increased by slumping of the fine bank sediments following floods.

Sediment Deposition

Woodyer *et al.* (in press) determined mean rates of accretion on benches (other than concave-bank benches) near Walgett. In one case the mean rate was 28 mm per year over an estimated period of 116 years. In the other case the mean rate was 27-57 mm per year for a period that could have been 8-17 years. Subsequently data have been collected (Table 2) by measuring the depth of sediment deposited on steel pegs driven flush with the surface. These rates vary from 9 to 26 mm per year (Table 2). In view of these additional measurements and the uncertainty about the period of deposition (8-17 years), the upper rate of 57 mm per year should be discounted. Therefore rates of deposition of 9-28 mm per year for these benches seem more appropriate. These rates compare with mean rates of 48-64 mm per year for the concave-bank benches.

DISCUSSION

It is apparent that the Darling River is a suspended-load stream. Moreover, the suspended sediment is dominantly wash-load consisting of silts and clays with 80-95% finer than 2 μm. In view of this, it is surprising that deposition occurs at high rates (9-64 mm per year) within the channel. Obviously some form of coagulation of the individual particles is necessary to permit deposition.

Partheniades (1971) found that, below a critical shear force, floccules of fine cohesive clays are not disrupted and so deposit. This concept appears to fit the deposition of muds in the Darling system. For example, rapid deposition (48-64 mm per year) of mud occurs on concave-bank benches (Woodyer 1975). Some 46-60% of the deposited sediment, when dispersed, is finer than 2 m and 85-90% is finer than 62 μm. This deposition occurs in gentle reverse flow, where the shear forces are low. The high proportion of clay (dominantly montmorillonite with minor amounts of kaolinite and illite) also suggest the likelihood of flocculation. Norrish and Quirk (1954) and Blackmore and Miller (1961) showed that calcium montmorillonite exists in 'packets' of 3-9 clay platelets. Shainberg and Otoh (1968) found that the introduction of sodium did not cause the breakdown of these packets until the sodium fraction reached 10-15% of the exchange capacity of an originally pure calcium montmorillonite. In four samples of sediment from the concave-bank bench exchangeable sodium plus potassium comprises only 4.8% of the total cations. On this basis it seems likely that deposition of mud, in quiet backwaters, is due to flocculation. This would not be 'salt water flocculation' (Partheniades 1971) since the concentration of solubles is less than 200 p.p.m. during these high flows in the Darling River. The dominant interparticle bonding is probably electrostatic attraction between the negatively charged faces and the positively charged edges of particles.

The deposition of montmorillonitic clays stabilises the channel. Woodyer *et al.* (in press) found that the channel had not shifted significantly since 1880 in a 30-km reach downstream of Walgett. Riley (1975) showed similar data for a number of sites on the Namoi, Gwydir and Barwon Rivers plotted in the 'straight' field of an Ackers and Charlton (1970) plot of stream slope versus discharge. Because these streams are 'meandering' and not straight Riley claimed that either the Ackers and Charlton line is not generally applicable or the Namoi-Gwydir streams are not in a 'live-bedded' condition. Taylor and Woodyer (in press) concluded that, although much of the channel of the Barwon-Darling River has a 'live bed', it has become fixed in a sinuous form, which

PLATE 12

(Above) The Darling River channel downstream of Bourke where the cross-section was surveyed and where the channel sediments were sampled. The picture was taken looking upstream and shows low amplitude sand dunes on the bed.

(Below) Aerial view of hairpin bend in the Darling-Barwon River 1.7 km downstream of Combadery gauging station showing locations of cross-sections where suspended sediment samples and bed-material samples were collected in 1969. The locations where samples 4 and 5 were collected are also indicated.

reflects its past history when it was a typical meandering channel. It appears that a channel has to have 'live banks' as well as a 'live bed' to fit the Ackers-Charlton classification. The deposition of montmorillonitic clays on the banks effectively stabilises them under the present flow regime.

Deposition of sediment within the channel in association with the growth of the ti-tree (*Melaleuca linariifolia* Sm.) tends to block the channel. Woodyer *et al.* (in press) concluded that at certain places and times this blocking effect leads to the formation of anabranches. This may explain the variation in form along the present channel from straight to sinuous reaches.

Preliminary analysis of suspended sediment data supplied by the New South Wales Water Resources Commission indicates that the peaks of sediment concentration lead the flood peaks. During the March-April flood of 1971 at Menindee this lead was 34 days. Heidel (1956) reported wash-load sediment peaks progressively, lagging the flood-wave. Whatever the explanation for this difference in behaviour, it is apparent that wash-load sediment peaks are not closely associated with flood peaks. In contrast, the peak concentration for suspended bed-material is likely to remain more constantly associated with the flood peak. This statement is based on the fact that the sediment peak of suspended bed-material is related to the greatest energy gradients. These maximum energy gradients remain more constant in their association with the flood peak than does the wash-load sediment peak. Thus the peak concentration of suspended bed-material is likely to occur at higher stages (up to the flood peak) than a wash-load sediment peak. This fact, plus the high percentage of sandy sediments in suspension in streams in which bed-material suspension predominates, may be related to the formation of levees along channel margins. It may be significant that there are no natural levees along the Darling River, a wash-load stream. In contrast levees occur on tributaries upstream of where they have dumped sandy bed-load (as mentioned previously). In a wash-load stream the sediment peak occurs well below the flood peak and below bankfull level (Wolman & Leopold 1957, Fig. 65) and the percentage of sand in suspension, particularly at higher stages, is low.

CONCLUSIONS

The channel of the Darling displays similar downstream trends, in respect to depth, sinuosity and silt-clay percentage, to at least one other channel in the Murray catchment, the Murrumbidgee River. This river was selected for comparison because the data was available. The main difference is the downstream decrease in width along the Murrumbidgee with decreasing discharge, whereas width increases downstream on the Darling River with the normal downstream increase in discharge.

The Darling normally carries a very fine suspended load. Sampling during near-bankfull flows failed to capture suspended sediment coarser than 37 μm. Suspension of fine to medium sands, deposited in bench sediments, must be very intermittent. However the steeper highland tributaries carry sand in suspension to a much greater extent. Much of this sand is dumped where these tributaries enter the western plains, forming distinct levees which are absent downstream along the Darling.

The bed material varies greatly in size distribution from sand to mud. The fine sediments occur mainly in the pools at bends, where the fine wash-load deposits during periods when discharge ceases, and near the banks where slumping has occurred.

Rates of deposition are estimated as 9-26 mm per year for point benches and 48-64 mm per year for concave-bank benches. These high rates of deposition suggest that flocculation of the fine suspended sediment occurs. This flocculation is probably related to the nature of the clay minerals (dominantly montmorillonite) and the adsorbed cations. Salt-water flocculation is ruled out because of the low concentration of dissolved solids (less than 200 ppm). Deposition of the floccules occurs in quiet backwaters where bed shear forces are low. These are often zones of reverse flow.

The deposition of these montmorillonitic clays on the banks has stabilised them and the present sinuous channel form reflects the past history when the river had a typical meandering channel. Blocking of this channel by sediment deposition associated with the growth of ti-trees in the channel has led to the formation of anabranches.

The occurrence of levees along streams may be related to the behaviour of the suspended sediment peak in relation to the flood peak and the calibre of the suspended sediment. The maximum sediment concentration of wash load leads the flood peak along the Darling River. As a result the sediment peak occurs below the flood peak and probably below bankfull level. The occurrence of the sediment peak at relatively low stages and the fineness of the suspended sediment may explain the absence of levees along the Darling. In contrast, where the sediment peak consists of sandy bed-load in suspension the sediment peak occurs near the flood peak at higher overbank stages. This associa-

tion of the sediment peak with the flood peak favours overbank deposition of sandy bed-material adjacent to the channel to form levees.

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14

THE GENERAL DISTRIBUTION AND CHARACTER OF SOILS IN THE MURRAY-DARLING RIVER SYSTEM

By B. E. BUTLER* AND G. D. HUBBLE**

GENERAL CHARACTER OF THE REGION

A brief general appraisal of the soils occurring over such a large area as the Murray-Darling River System demands stringent condensation of the actual soil variations. The area for consideration is approximately 800 by 1,250 km (see Fig.1) and, within a few metres in many instances, the soil varies markedly. Condensation would be effected by classification to the higher categories of any one of the several classification systems which are available, if the differentiae of the taxonomic classes bracketed the local variation in actual areas. But this cannot be counted on, and the best condensations are made on the criteria of their juxtaposition in the landscapes in which the soils are found.

Fig. 1 shows some of the main landscapes of the Murray-Darling System, in particular the depositional riverine plains and the areas characterised by sand dunes. The system is peculiar in having two separate riverine plains across which tributary streams flow, gathering into trunk streams which then traverse plains of a non-riverine character, dominated by sand dunes. The tributaries rise in high rainfall, mountainous country on the south and east of the system, and the trunk rivers flow into land of diminishing rainfall, from which there is little or no contribution to flow, but rather a loss. Some of the northern tributaries rise in less mountainous, lower rainfall country than the eastern and southern tributaries.

The southern riverine plain has been previously named the 'Riverine Plain of South Eastern Australia' (Butler 1950), and this name will be used here. The northern riverine plain will be called the Darling Riverine Plain. It will be noted in Fig. 1 that the Riverine Plain of South Eastern Australia is abutted immediately on the west by the dune lands (here inscribed Murravian Gulf from the marine incursion in this area in Tertiary time). In contrast the Darling Riverine Plain has a fringe some 300 km wide of undulating country separating it from dune lands to its west and southwest. This fringe will be referred to as the Bourke Tableland; it contains a number of ranges of low hills only a few of which are named. The Grey Range and the Main Barrier Range form the western boundary.

Knowledge of the soils throughout the Murray-Darling System is very uneven: the best known parts are generally to the south and on the riverine plains. The soils will be discussed collectively for each of the provinces in turn, the provinces being the subdivisions mentioned above and indicated in Fig. 1.

THE SOILS OF THE RIVERINE PLAINS

Extensive studies of soils and landscape in the Riverine Plain of South Eastern Australia (Butler 1950, Butler *et al.* 1973) have led to the condensation of soil and landscape variation into the characteristic sequence shown in Fig. 2. This represents a transect of soils, adjacent pairs of which are found to occur in nature adjacently, and in the shown topographic relationship. This characteristic sequence of soils is associated with 'prior streams', deserted sedimentary structures issuing in radial pattern from the debouchment of each tributary stream onto the riverine plain.

(a) *The Soils of the Riverine Plain of South Eastern Australia* are depicted in the characteristic soil sequence in Fig. 2. There is an overall grading from sand to heavy clay in the span of the sequence, an overall increase in soluble salts and base saturation, and a span in colour from red-brown to grey. The soils show well-contrasted profile differentiation, with eluviation/illuviation of clay and lime indicated. The full span of soils is earthy red sands, to sandy red-brown earths (Stace *et al.* 1968)

*CSIRO Division of Soils, P.O. Box 639, Canberra, A.C.T. 2601
**CSIRO Division of Soils, Cunningham Laboratory, Mill Road, St. Lucia, Queensland 4067.

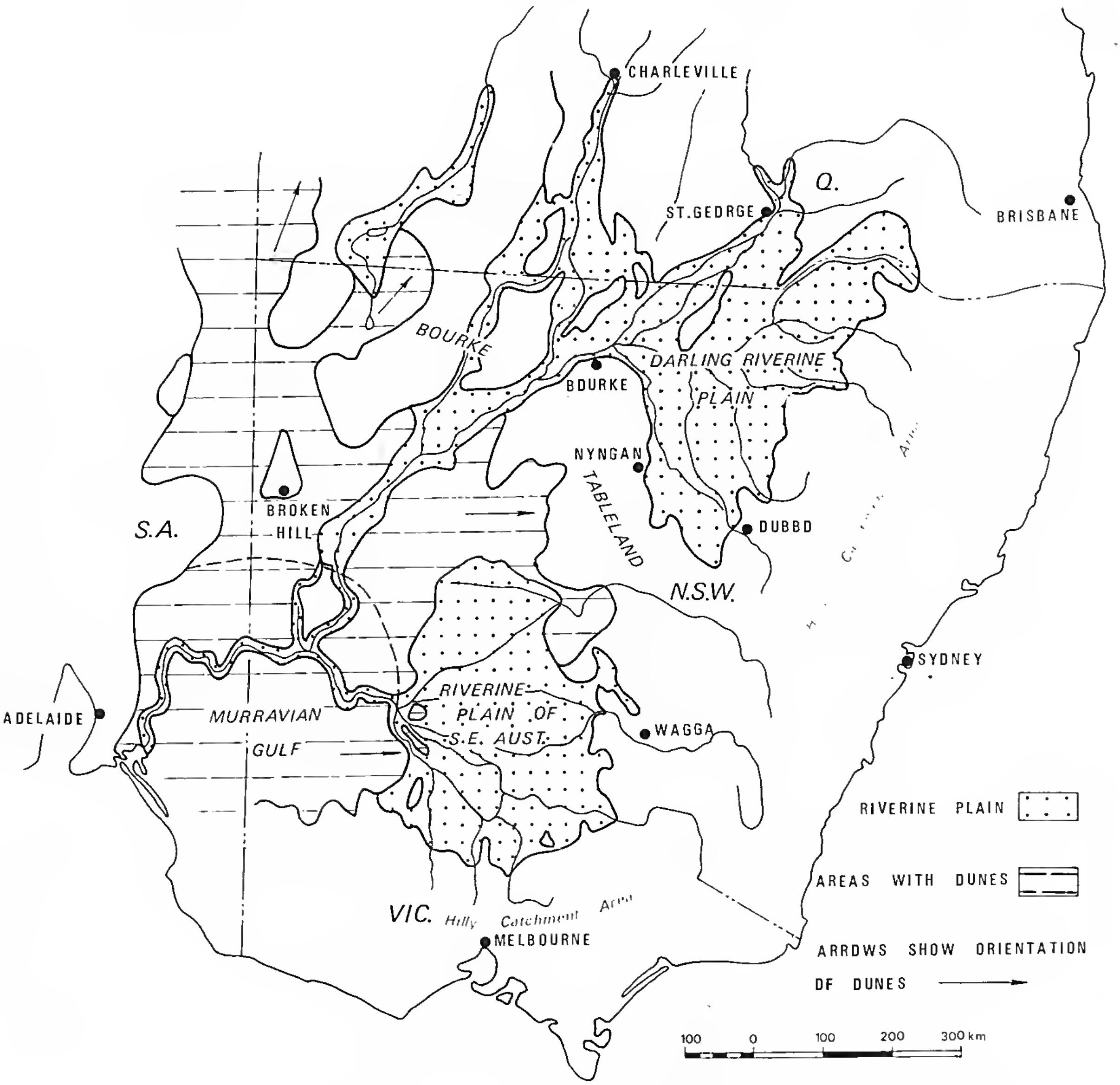

FIG. 1 — Murray-Darling River System showing landscape features. Compiled from data from Northcote *et al.* (1975) and Löffler and Ruxton (1969).

to red-brown earths to brown and grey clay soils of significant salinity.

This characteristic sequence of soils is applicable to all of the alluvial fans of the tributary streams of the Murray system: Murrumbidgee, Murray, Ovens, Goulburn, Campaspe and Loddon Rivers. Though the lithology of the catchments shows some variation, chiefly in the basalt present in the Loddon catchment, there is no significant soil variation on the plain associated with it.

(b) *The Soils of the Darling Riverine Plain:* Soil studies have been made of the Macquarie alluvial fan (Downes & Sleeman 1955), of the Namoi (Stannard & Kelly 1977), the Gwydir (Stannard & Kelly 1968), the MacIntyre River, Moonie River (Isbell 1957), and the Balonne and the Maranoa Rivers (Gunn 1974). Though there are numerous grounds supporting a prior stream proposition for this riverine plain, the component soils show a different proportion and character from their counterpart in the Riverine Plain of South Eastern Australia. Not only are the soils different from those down south but each alluvial fan of each tributary may differ in its own way.

The soils of the Namoi alluvial fan (Stannard & Kelly 1977) have a prior stream pattern, but the proportion of red-brown earths in the section is small, and most of the transect is taken up with grey self-mulching soils. Stannard & Kelly (op. cit. p. 87) state that the salt content of the soils is lower than for equivalent soils in the Riverine Plain of South Eastern Australia, and the salt does not increase with distance down the prior stream as it does in the south. These clays of the Namoi system compare with those of the Barwon further west, which are illite-kaolinite but less self-mulching. The Namoi clays have a high proportion of montmorillonite, and their particular characteristics are associated with the significant proportion of basalt in the catchment. The Barwon clays are associated with the more northern tributaries, the MacIntyre, Moonie, Balonne etc, and with their catchment areas and their mantle of Tertiary weathering.

The Gwydir alluvial fan and catchment have similar characteristics to those of the Namoi (Stannard & Kelly 1968) but the Macquarie is different in having a high proportion of red-brown earths in its alluvial fan (Downes & Sleeman 1955). In this it is like the alluvial fan of the Murrumbidgee River, and unlike those of the Namoi and Gwydir Rivers. There is very little basalt in the catchment of the Macquarie River.

Information on the south-flowing tributaries of the Darling Riverine Plain is less complete than for the west-flowing tributaries. Main sources are Isbell's (1975) study of the MacIntyre and Moonie section, and Gunn's (1974) for the Balonne and Maranoa. There are differences in overall pattern in that the riverine deposits are valley plains, and coalescing valley plains, rather than the coalescing alluvial fans of the west-flowing tributaries. There are other differences including the occurrence of some terraces and some variation from the prior stream form. However there are deserted stream structures with sandy soils merging to plains of grey cracking clays. A conspicuous feature is the solodized-solonetz character of the soils at the sandy and mid-textured section of the sedimentary spectrum. These are soils with abrupt and highly contrasting A horizon — B horizon contrast and interfaces, a marked dominance of Mg on the exchange complex, and a variable tendency toward exchangeable Na and salinity in the lower horizons. The solodized-solonetz soils form a significant proportion of the characteristic soil sequence and take the place of red-brown earths in Fig. 2. The salt and sodium characteristics of this spectrum of soils are apparent to only a moderate degree in the eastern tributaries but increase in the more western, low rainfall section.

The source areas of these streams and their sediments are the deeply weathered Tertiary landscapes of southern Queensland where typical soils are residual red earths, often lateritic, loamy solodized-solonetz soils, and brown and grey undulating clay plains on bleached weathering zones. Kaolinite is the dominating clay mineral.

In summarising the soil array of the two Riverine Plains, it may be noted that whereas there is a marked degree of uniformity among the alluvial fans of the Southern Riverine Plain, the Darling Riverine Plain varies in a number of ways, with differences there between one alluvial fan and another. The south-flowing tributaries are marked by the occurrence of solodized-solonetz soils, whilst the west-flowing tributaries are marked by the character and dominance of their grey self-mulching clays. Both peculiarities seem to be associated with the character of their respective catchments.

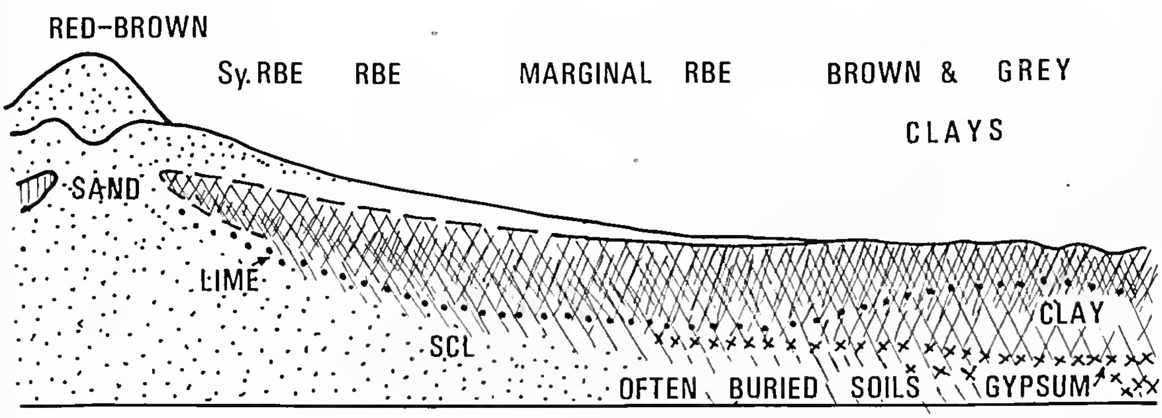

FIG. 2 — Characteristic soil sequence: Riverine.

SOILS OF THE DUNE LANDSCAPE

The dune landscape in the region is most frequently characterized by parallel, linear dunes. These have consistent orientations in each locality. Each reflects the direction of the dominant local aeolian movement, as shown by the arrows in Fig. 1. There is variation from locality to locality in the amount of sand, its colour, and the proportion of sand to associated clay and lime. Where there is most sand the dunes are close together and irregular, and where it is least and verging on absence sparse coppice dunes take the place of linear dunes. Though the proportion of clay and lime in the dunes may vary without affecting their shapes, the specific clay dunes adjacent to dry lakes are exclusively of crescentic shape.

Fig. 3 is the characteristic soil sequence for the dune transect. It is largely based on experience in the Murravian Gulf section of the dune field areas. The areas of dune field further north in the region are not so well known. Fig. 3 is a section transverse to the length of the dune, and extends half way across the adjacent flat or swale. There is a marked sorting of material, with maximum of sand at the crest of the dune, and maximum of clay, lime and salt in the central swale position. Soil profiles generally show a marked eluvial-illuvial segregation of clay, lime and salts, usually with gradational changes (Gc of Northcote 1971), though further out on the swale Drl and Ug (grey cracking clays) may be present. Where these well-differentiated profiles are found the dunes have obviously been stable for a pedologically significant period. However since the dune zone extends into very low rainfall area, some dune areas would have a shorter or nil record of stability, and then soil profiles would be less differentiated.

Mention must be made of the dunes which are frequently found associated with dry lakes and clay pans in the Murravian Gulf area. These are crescentic in shape, hugging the eastern side of the lake. Usually they are clays, and have come to their place as saltating clay aggregates from the adjacent lake floor when this was dry.

A local character in dunes results from their origin in the wind erosion of local materials. Any coarse component remains as lag gravel, the saltating sand accumulates as local dunes, and only the dust component travels long distances. It may move long distances down wind and become so mixed as to assume a regional character. It would be expected that the components, lag gravels, dune sands and dust or parna, would be different in the northern dune areas where Tertiary weathering zones are the source, compared with the parna and other components having their origin in the Murravian Gulf area. In addition to difference in composition there would be a difference depending on the hardness of the country i.e. its susceptibility to wind erosion. Much of the old Tertiary weathering material is hard and concretionary or otherwise indurated, whereas materials of the littoral environment, especially calcareous and saline clays in the Murravian Gulf area, are likely to be soft and granular when dry.

SOILS OF THE PARNA-MANTLED LANDSCAPE

The dust component of wind erosion-sedimentation process is regionally recognised as parna, an aeolian clay (Butler, 1956). It has been identified and studied at a number of places in and adjacent to the Riverine Plain of South Eastern Australia. Churchward (1963) studied parna at

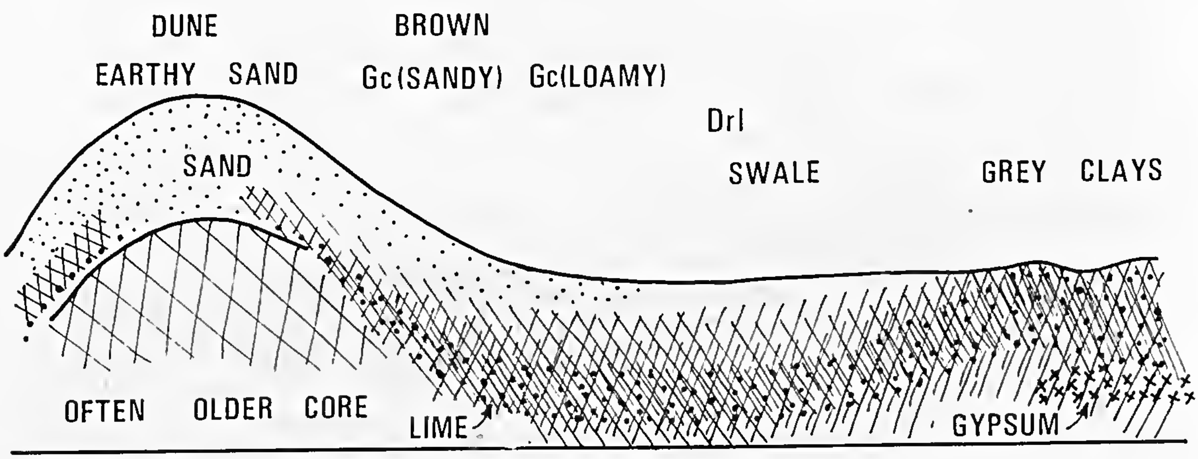

FIG. 3 — Characteristic soil sequence: Aeolian.

Swan Hill with regard to its source in the wind erosion of soils and its graded distribution in the structure of sand dunes. Van Dijk (1958) identified parna at Griffith, both as a mantle overlying riverine beds on the plain and as a mantle on the adjacent hillslopes. Sleeman (1975) studied the parna mantle on the granite hills of Pyramid Hill in relation to the mineralogical contrasts between it and the substrate. Beattie (1970, 1972) studied the parna on the hillsides at Wagga Wagga giving particular attention to its peculiar characteristics: sub-plasticity, basicity, dolomite and baryte concretions and palygorskite cutans. Beattie (priv.comm. 1977) has also examined the contrast in Ti/Zr ratio of the parna and of the underlying weathered granite at Wagga, and finds them significantly different at the 0.1% level.

The separate identity of the parna can be proved where it mantles the hills, but proof is not so convincing on the plain. However its occurrence at widespread points like Swan Hill, Pyramid Hill, Griffith and Wagga Wagga leads to the inference that it was also spread over the intervening plain. Experience in soil survey had already lead to this conclusion (Butler 1958). Soil surveys at Rutherglen suggest the occurrence of parna there, (Poutsma & Skene 1961) and the occurrence of the array of soils in Fig. 4 at Dookie near Shepparton (Downes 1949) leads us now to the proposition that parna mantles the slopes and plain there.

The occurrence of parna as a widespread mantle on the riverine structures and sediments of the Riverine Plain of South Eastern Australia could well impose the unified character of the soils of the several alluvial fans which are found there, and which is in contrast to the variation of soils in the alluvial fans of the Darling Riverine Plain.

The characteristic sequence of soils for the parna from the Murravian Gulf region is shown in Fig. 4. Parna, like loess, takes the form of the substrate, and the main theme of variation in soil profile depends on the drainage status of the site. In the well-drained, elevated position the profile is a red earth with gradual build-up of clay with depth, sub-plastic properties in the sub-soil clay and leaching of alkaline earths. The soil in the level to slightly sloping site is a red-brown earth with clay and lime B horizons and tending toward a solonized profile in the flatter position. In the flat or depressed positions the soils are brown and grey clays, self-mulching, gilgaied and calcareous. These soils often contain gypsum and appreciable soluble salts at depth as do also, to a lesser degree, the solonized red-brown earths.

The parna mantle is characteristically high in clay, in alkaline earths, and significantly salty: however it has been in place long enough for marked leaching and soil development to have occurred where the drainage of the site favours this.

SOILS OF THE NORMAL HILLSIDE SEQUENCE

In the greater part of the catchment of the Murray-Darling System, especially on the east and south, the soils fit a general sequence shown in Fig. 5. This sequence varies with drainage, and has red earths and red-podzolics in the well-drained sites, and yellow podzolic and gleyed-podzolic soils in the

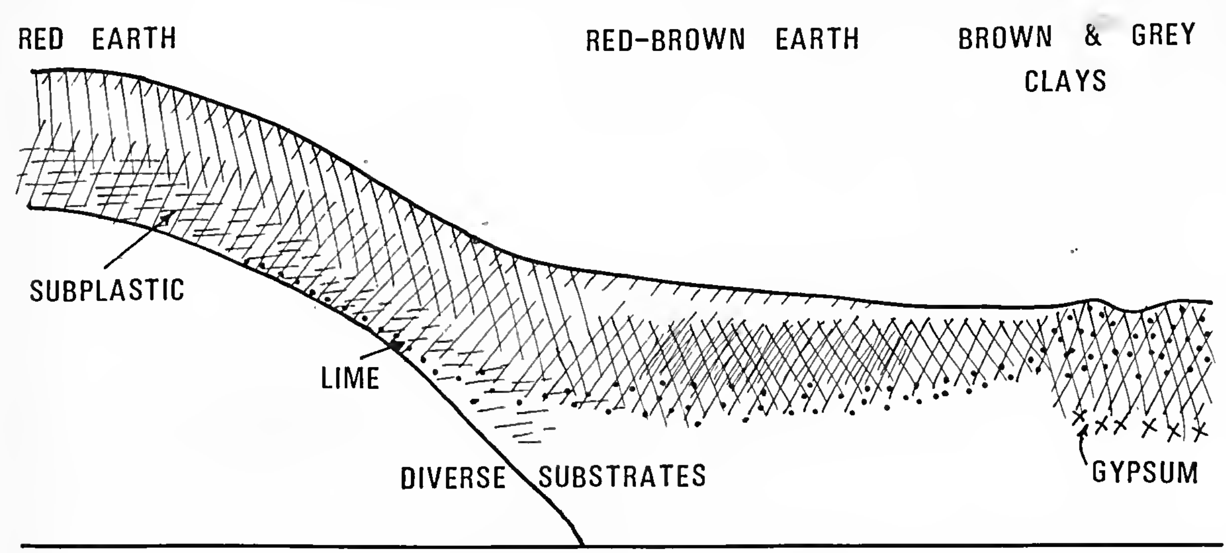

FIG. 4 — Characteristic soil sequence: Parna Mantle.

poorly drained areas. There may be a tendency toward solonized conditions and lime in some of the poorly drained sites.

There are many variants from this sequence due to parent material differences: hardness, thickness of the mantle, age, degree of horizon contrasts. The main contrasts from our point of view are differences associated with basalt as a parent material, and those due to Murravian Gulf parna as a parent material. The basalt sequence (except for old weathering) is characterised by black earth soils at the drier and poorly drained end, and krasnozems and chocolate soils at the well drained end. The parna sequence should be easily distinguished from the 'normal' hillside sequence, especially by its poorly drained member. Though there are some similarities between the parna sequence and the basaltic sequence, these are hardly likely to cause confusion in practice.

THE DISTRIBUTION OF PARNA IN THE MURRAY-DARLING SYSTEM

The distribution of parna from the Murravian Gulf region is roughly indicated, at least on the south and east. The dune orientation (shown in Fig. 1) indicates an easterly extent from the Murravian Gulf area, but there is little evidence of its extending far to the east of Wagga Wagga. There is evidence of parna in the Macquarie alluvial fan, to the west and northwest of Dubbo, in the extent of red-brown earths there as shown in the soil maps of Downes and Sleeman (1955). Their maps show also 'brown acid soils' on the Bourke Tableland north and south of Nyngan, and the characteristics of these conform to the red earth sub-plastic member of Fig. 4. Further suggestion that these soils are formed on parna is to be found in the observation of Downes and Sleeman (1955, p.23) that their brown acid soils occur on both alluvial and stony substrates. From the present senior author's observations, evidence for parna similar to that at Griffith occurs on the Bourke Tableland out as far as Bourke. But there is no evidence for parna elsewhere in the Darling Riverine Plain. The individual character of each alluvial fan precludes any general spread of parna there.

The question of parna occurrence in the northwest of the Murray-Darling System is an open one, though the dune landscapes suggest it. The orientation of the linear dunes indicates a northeasterly, not an easterly extension, and the absence of parna from the Darling Riverine Plain is perhaps not surprising, as that region is at the place where the change of directions of the wind system would tend to disperse or attenuate any dust deposit. However parna may be sought on the western portions of the Bourke Tableland. As mentioned above, it should there have a character determined by the soils of the Tertiary weathering zones which are its source there. These would be dominantly kaolinite clays, perhaps rather low in lime. Dominant soils in the Bourke Tableland area according to Northcote *et al.* (1975) are 'red earths', and show extensive uniformity of type, notwithstanding the variety of the substrates. These red earths are not necessarily different from the Downes and Sleeman 'brown acid soils' mentioned above. Further west many of them are described as residual 'hard' mulga soils and are clearly associated with the old Tertiary land surfaces. But

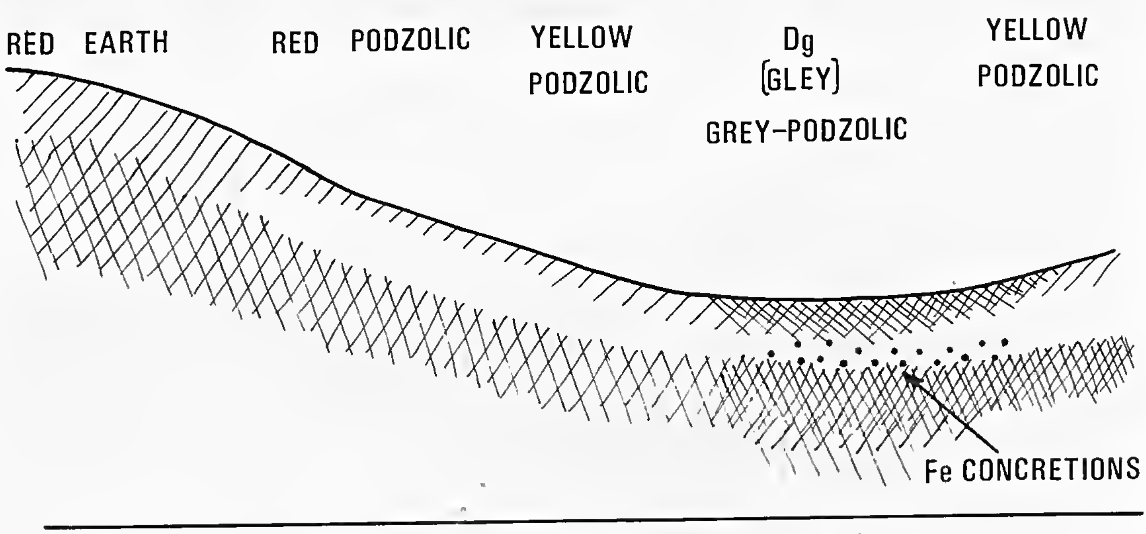

FIG. 5 — Characteristic soil sequence: Hillside.

other areas are described as 'soft' mulga country and could possibly be regional parna. This would be the well-drained member of the sequence; the poorly drained member would probably be a solonized red-brown earth. Lime and soluble salts, though present, are probably less than in the soils of the Murravian Gulf parna.

FURTHER CONDENSATION OF THE SOIL DATA

The foregoing condensation of soil data for the Murray-Darling River System has been based on the characteristic sequence of soils for the several landscape classes into which the area is subdivided. The characteristic sequence show the soils which are found adjacent to one another most often, and the topographic change associated with such soil transitions. The soil changes are of two kinds: those associated with texture change (sand to clay) and those associated with slope and topographic position of the site. In the riverine sequence and the dune sequence these two variables coincide, but in the hillside sequence and the parna mantle sequence there is only the slope variable. The operation of this variable gives the range of states understood by soil workers as variation in the 'leaching' factor: the sloping, elevated sites are highly leached, the flat or depressed sites poorly leached. The characteristic sequence of soils in all cases spans the range from highly leached to poorly leached. This is indeed the main local soil variable, and it is associated with topographic change.

If we disregard these variations at the next higher level of condensation we are left with a limited realm of variation such as can be seen in passing transversally from one characteristic sequence to the other at (say) the second position from the left of Figs. 2, 3, 4, and 5. At such a transect the soils are rather similar and the differences that persist can be related to parent material differences. In the range of parent materials occurring in the Murray-Darling System the following may be singled out:
(i) The parna of the southern portion, high in clay, alkaline earths, moderate in soluble salts.
(ii) The Tertiary weathered material of the north-western and northern portion of the area, high in kaolin clay.
(iii) The 'normal' parent materials of the catchment areas beyond the effects of (i) and (ii).

The parna of the southern portion has been typified, in its red earth profile, by Beattie (1970). It is a kaolinite-illite clay with evidence, though leached, of high basicity, including the segregation of palygorskite. The typical red-brown earth profile has been leached of much of its basicity, but remains alkaline. Exchangeable cations show Ca and Mg roughly equal but with reciprocal trends in depth (illustrated in Table 1 by entry 2 from Griffith).

The Tertiary weathering, whether in-situ as alluvial deposits, or (presumably) as wind-sorted deposits, is typified by kaolin and the solodized-solonetz soil profile. In this profile the contrast and transition from A to B horizon is still more marked

TABLE 1

EXCHANGEABLE CATIONS OF SOIL PROFILES REPRESENTING THREE PARENT MATERIAL CLASSES

Location	*Depth (cm)*	*Percent of exchangeable cations as:—* Ca	Mg	Na
1. Gwydir irrigation area.* (Montmorillonite)	0–10	79	14	2
	10–20	85	8	1
	20–30	77	12	10
	30–46	68	17	7
	46–60	75	9	13
2. Griffith.** (Kaolin, illite)	0–18	66	24	1
	18–48	54	37	2
	76–100	39	44	10
3. Inglewood.*** (Kaolin, montmorillonite)	0–15	32	51	10
	15–25	43	46	10
	25–38	6	67	26
	38–76	3	66	30

* from Stannard & Kelly (1968), ** from Taylor & Hooper (1938), *** from Isbell (1957).

than in the red-brown earth, and the tendency for exchangeable Mg to increase at the expense of Ca is still greater, as shown in Table 1, entry 3 from Inglewood.

The 'normal' parent material can not be defined, but in this study it is interesting to refer the characteristics of the two above-mentioned parent materials to the soils formed on basaltic alluvium in the Namoi and Gwydir alluvial fans. The representative soil there is a grey self-mulching clay, a montmorillonite clay, with exchangeable cations, dominated by Ca as shown in Table 1, entry 1. Without claiming that this is typical of the whole catchment area it is evident that the cyclic accession of salt in the environment, and the geomorphic set-up, do not in themselves make the solodized characteristic of soils, as Downes and Sleeman (1955, p.43) propose. Parent material is also a factor.

The three parent material classes proposed for the region are typified in Table 1 by their exchangeable cation profiles. These are probably a reflection of the complex of clay minerals in each type of parent material. There is a broad uniformity of parent material over large areas of land when these parent material classes are adopted. They are natural sub-divisions for the region because they fit the history of the region in terms of the distribution of parna, the long-time stability of landscape surfaces, and the contrasting normal.

ACKNOWLEDGMENTS

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SOILS OF THE UPPER VALLEYS OF THE MURRAY RIVER BASIN

By R. K. ROWE*, R. J. CROUCH† AND D. C. VAN DIJK‡

ABSTRACT: The landscapes and soils of the valleys of the Upper Murray River and its main tributaries in New South Wales and Victoria are described.

These areas have a complex topography which comprises a low central, clearly terraced alluvial belt, a higher multi-stepped gently sloping fringe of more or less dissected alluvial-colluvial fans, and broadly rounded spurs, ridges and hills. At their outer edges, the valley slopes grade up sharply to the steeper slopes of the confining ranges.

Studies of the relationships between soils and landscape features have been assisted by the use of a conceptual framework of soil-geomorphic units, referred to as 'pedo-morpholiths'.

Soils of the flood-plain are usually stratified and undifferentiated, whereas on slightly older bodies of sediment the soils are weakly differentiated, and may have gradational profiles. The most widespread soils on the older, upper terraces and fans and the less steep residual hills are red and yellow duplex soils. Gradational soils are also well represented in these areas in a range of situations which indicate they are of different ages. A common feature of this area of older land forms is that surface soils are often found to overlie truncated remnants of older soils.

In areas where average annual rainfall is above about 650 mm, the soils are typically quite acid and free of lime. In the drier areas however, free lime may occur in the subsoil.

Because the soils of the alluvial-colluvial landscapes are generally deep, and occur in areas of relatively high and reliable rainfall, they are widely used for agricultural production.

INTRODUCTION

This paper describes the soils and valley landscapes of the Upper Murray River and its main tributaries, the Swampy Plains and Tooma Rivers in New South Wales and the Mitta Mitta, Kiewa and Ovens Rivers in Victoria. (Fig. 1).

Factors Affecting the Soils

Soil characteristics and the distribution of the different soils are dependent upon the nature of the material in which the soils are formed, the topographic setting, the climate over the period of soil formation and the length of time that the material has been exposed to the biological and physical processes which have operated. To understand the differences between the soils and their distribution it is necessary to know something about these factors.

Within the area under consideration, the present-day rainfall ranges from about 500 mm in the relatively dry, warm areas in the west to about 1000 mm in the cooler higher rainfall areas in the sheltered upper valleys in the east and south.

The rocks from which the soil parent materials are derived include granodiorite, granite and Palaeozoic non-calcareous sedimentary rocks, much of which have been metamorphosed to gneiss or schist. Most of the soil parent materials in the valley landscapes are transported and occur as fans and terraces, and even on hill-slopes there is commonly a mantle of colluviated material. The stratgraphic relationships of these bodies of sediment allow relative age sequences to be identified.

The Geomorphic Setting

In cross-section each valley landscape shows a characteristic sequence of topographic units, schematically shown in Fig. 2A. The broad, low-relief valley plains of smaller stream systems which

* Soil Conservation Authority, 378 Cotham Road, Kew, Victoria 3101.
†Soil Conservation Service of New South Wales, Wagga Wagga, N.S.W. 2650.
‡CSIRO Division of Soils, Cunningham Laboratories, Mill Road, St. Lucia, Queensland 4067.

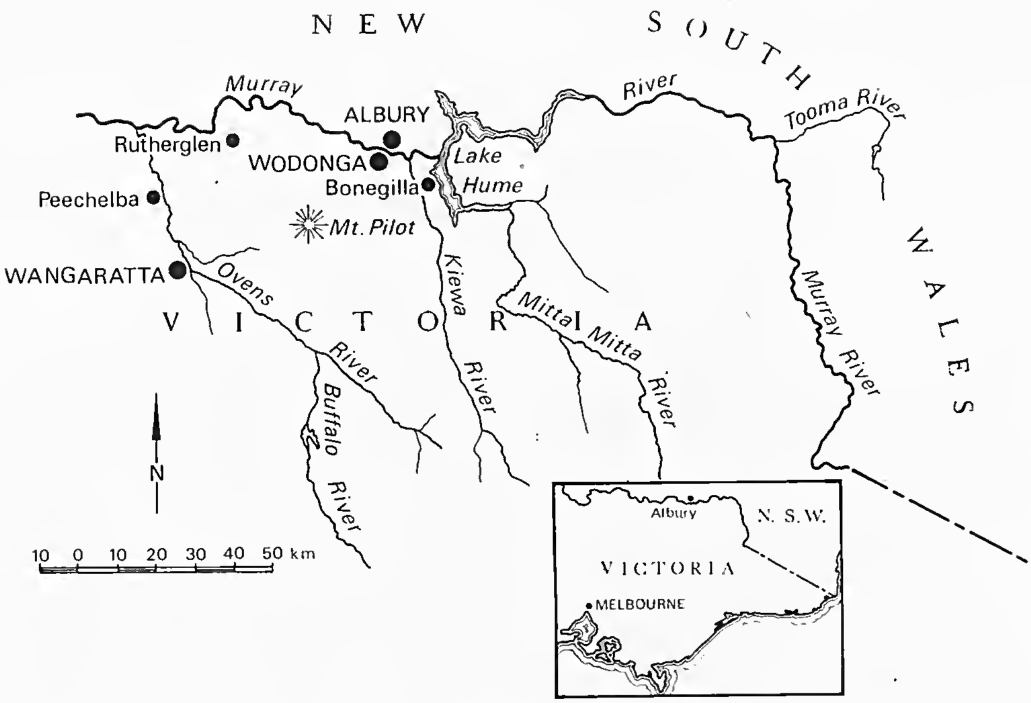

FIG. 1 — Location plan.

characterize in particular the country north of Albury show the same sequence, although the topographic units occur in different proportions. The latter sequence is shown in Figure 2B.

All the major valleys and many of the tributary streams have flood plains which are regularly flooded and still receive regular accessions of sediment.

A flood plain is usually dissected by abandoned meander channels which in many cases retain water for much or all of the year. There may also be sandy levees associated with the present stream channel and some of the abandoned channels. A feature of the flood plain is that the channels of tributary streams are often located on its outer edge for some distance before entering the trunk stream. These features influence the distribution and character of the flood plain soils.

The flood plains are bordered by a set of alluvial terraces, the lower two of which may be well represented although their respective proportions vary considerably in any one valley. In some areas small benches of stream alluvium are found at even higher levels on the valley sides. The area around Bonegilla — Hume Weir, where the Mitta Mitta and Kiewa Rivers meet the Murray, has several such high level alluvial deposits.

Extensive terraces some 10-15 m above the entrenched flood plain and low terrace set are a prominent feature of the lower Kiewa valley, the Murray valley west of Albury and the Ovens valley below Wangaratta where they form extensive valley plains. Remnants of another terrace below the extensive valley plain, but well above the low terrace set, occur intermittently. A good example of this terrace is traversed by the Hume Highway for several hundred metres immediately east of the Reedy Creek bridge at Wangaratta North.

The extensive valley plain of the Ovens to the north-east of Wangaratta has a well formed prior stream system (Butler *et al.* 1973) which is readily identified on aerial photographs. A section of the prior stream channel, Wim Creek, still carries local drainage. A short section of a similar (or the same) prior stream system occurs to the west of Wangaratta, and other remnants can be identified upstream towards Tarrawingee and at Millawa. Butler *et al.* (1973) mapped another extensive prior stream system extending to the northwest of Corowa. Remnants of this system can be recognised as far east as Howlong.

Flanking the prior stream ridges on the Ovens are poorly drained clay plains which, to the north and east of Boorhaman, are quite extensive. The main prior stream system to the northeast of the Ovens loses its identity in a series of more-or-less parallel, sandy ridges which extend from Boorhaman north through to Brimin on the Murray near

its confluence with the Ovens. These appear to be an ancient dune system derived from sediment deposited at the confluence of these two major valleys.

In the mid to lower reaches of the main valleys, much of the less steep landscape within the confining ridges consists of complex fans of alluvium and colluvium. In broad valleys such as the Mitta Mitta at Noorongong and the Kiewa at Dederang, and near the junction of the Tooma with the Murray, the alluvial fan landscape constitutes a large proportion of the valley. As the valleys narrow upstream, a smaller proportion of the alluvial fan landscape persists, until in the upper reaches it is common for the flood plain and terrace landscape to abut directly onto the steep slopes of the valley sides where bedrock outcrops or is covered by a thin mantle of colluvium. Young colluvial fans may be present at the foot of the steep slopes.

The uppermost members of the alluvial fan sequence are well dissected, and fan-in-fan forms are common (Pl. 13, above). The toes of these older fans have, in most cases been truncated by the trunk stream (Pl. 13, below), which results in a more or less continuous irregular scarp some 5 to 10 m high at the outer edge of the lower alluvial terrace set. This feature is well developed along much of the Kiewa valley and in the Mitta Mitta valley. Valley-side drainage systems which traverse the fan landscape have dissected the scarp and young fans extend onto the upper members of the lower terrace set. The main components of the landscape are shown in Fig. 3.

The Sequence of Erosion, Deposition and Soil Formation

The relationship between the present soils and the geomorphic history has been examined by van Dijk and Rowe (unpubl.), and a conceptual framework of the sequence of erosion and deposition and soil formation developed. The approach requires a detailed consideration of land form, the nature of the sedimentary material and the soil and deep sub-solum features. Distinctive soil-geomorphic units have been referred to as *pedo-morpholiths*. The concept assumes that bodies of material transported at similar times have undergone similar weathering processes over similar periods, so that when lithologic, local topographic and regional climatic effects are allowed for, the pedogenetic and other weathering

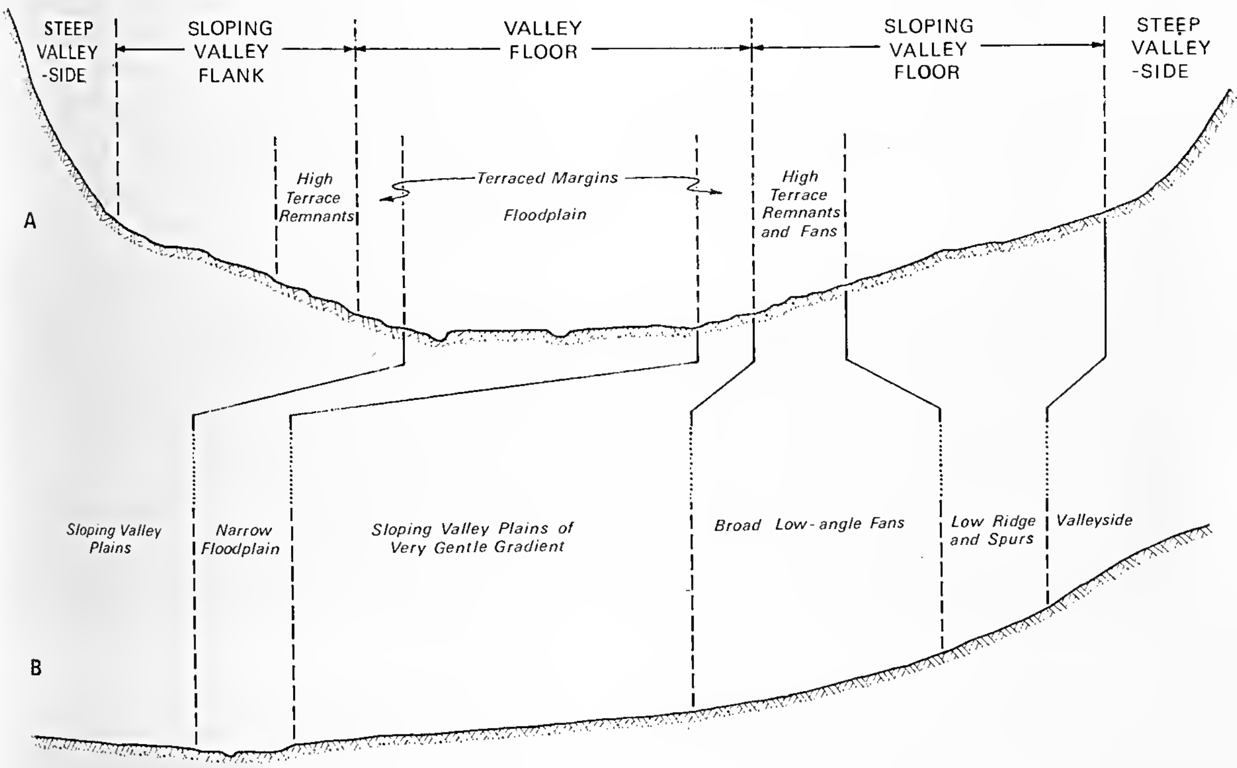

Fig. 2 — Schematic cross-sections of valley landscapes. A. Major valley of the highlands. B. Valley of the foothills.

features of such similar-aged bodies should have certain features in common. The approach is an attempt to enhance the predictive value of detailed landscape analysis for soil mapping.

The sets of terraces and the fan-in-fan formations indicate that periodic alternation between landscape erosion and subsequent stability plus soil formation has played a dominant role in developing the present valley landscapes. The agencies responsible for the periodic landscape instability have been changes in climatic patterns as proposed by Butler (1959) or regional tectonic activity which altered regional erosional base-levels.

Successive periods of erosion and deposition have modified the older landscapes to varying degrees, but the characteristics of the sequences of depositional bodies that exist in these valleys indicate that the general trend has been for each successive period of erosion to be less severe. As a consequence of the long history of periodic erosion, many of the older bodies of sediment have been greatly modified, and the more highly weathered and readily eroded materials have been truncated or in places, have presumably been stripped entirely.

This geomorphic evidence for periodic events in landscape formation is complemented by the widespread occurrence of buried soils.

Although the complexity of the present surface soil pattern is still difficult to interpret in detail, an understanding of the sequence of soil and landscape-forming events as provided by the pedo-morpholith framework helps substantially in extrapolating soil mapping from limited detailed site studies.

The Soil Patterns

Some general relationships are shown in Table 1 with reference to Fig. 3 to indicate zones which are identified with major stages in pedo-morpholith development.

There is a general trend from the youngest soils with minimal pedogentic alteration through increasing development of colour, texture and structure in B horizons in the soils on older materials. However, the trend does not persist to the oldest materials, where some of the soils have distinctly duplex profiles whereas others are gradational. The effects of surface stripping and burial may be evident in some of these duplex soils, and stone-lines, which can be interpreted as lag-layers formed by soil movement, sometimes mark the junction of the A- and B- horizons and may sometimes occur within the A-horizon.

There is a trend towards increased thickness of the B-horizon with increasing age but this can be upset where substantial stripping of the old soil has occurred, or when the original mantle of weathered material was shallow.

Within a specific landscape component, catenary effects occur. When moving from upper catenary positions to lower ones, such effects are, typically, changes from reddish to yellowish sub-soil colours, increased sub-soil mottling and sometimes development of ironstone concretions in soils in low situations.

The effect of climate is probably most evident in the changing soil reaction trends, as the most acid soils occur in the higher rainfall areas of the east, and soils with free lime in the subsoil are mainly found in the drier western areas. However, the present average annual rainfall over most of the area is above 650 mm and leaching of salts and free ions predominates over accumulation except in topographic low areas where drainage is impeded.

Previous Soil Studies

Much of the knowledge of the soils and their distribution in the area has been derived from broad-scale land-system studies by Rowe (1967, 1972 and unpublished data) on the Victorian side of the Murray. Newell (1970) made a detailed study of the soils of the alluvial landscapes in the central part of the Ovens valley between Wangaratta and Bright and in the Buffalo River. Except for the work of Newell, the wider valley landscape of the Ovens north of Whorouly has not been systematically examined. Crouch (1976) described soil associations and dominant soil groups on the Albury district. His work has been supplemented by localised detailed surveys around Albury and Howlong (Junor *et al.* 1977, Junor & Crouch 1977).

THE MAIN SOIL GROUPS

The primary profile forms of Northcote (1974) provide a convenient grouping of the soils on the basis of whether texture profiles are uniform, gradational or duplex. Organic soils, the fourth primary profile form of Northcote, occur in the alpine areas of the region, and do not occur in the area described in this paper. The names used for the soil groups are adapted from the Northcote primary profile forms to provide a descriptive nomenclature.

1. Soils of Uniform Texture

1.1 *Alluvial Soils.* These are the soils of the flood plains, and youngest terraces and alluvial fans throughout the Upper Murray. As they are formed on the youngest alluvium and lack biological

PLATE 13

(*Above*) The Mitta Mitta valley at Noorongong, showing a broad terrace in the foreground and fan-in-fan forms at the foot of the steep valley sides.

(*Below*) The lower valley of the Kiewa River. The older alluvial fans have been truncated and dissected. Younger fans emerge from the entrenched drainage lines and grade down to the upper member of the lower terrace set.

TABLE 1

THE BROAD PATTERNS OF SOIL AND LANDSCAPE RELATIONSHIPS.
(To be read in conjunction with Fig. 3.)

Soil Group	*Main Land-scape Zone*	*Distribution*
1. *Soils of Uniform Texture*		
1.1 Alluvial soils	F–F	Predominant on floodplain
	F–D	On youngest fans
1.2 Sandy loams	D–E	On young fans and hillwash sheets from coarse-grained rocks
1.3 Grey and brown clays	C–D	On slope mantle and fans
	E–G	Common on poorly-drained parts of high terraces or valley plain
1.4 Brown loams	F–F	On terrace remnants just above flood plain
2. *Gradational Soils*		
2.1 Reddish gradational soils		
.1 Soils with minimal B-horizon	E–F	On lower terrace remnants in this zone and occasional fans which overlie the upper terraces
	D–E	On fans; more extensive in upper valley tracts
.2 Soils with well developed B-horizon (friable)	B–E	On older fans, high terrace remnants in upper valley tracks and deeply weathered old surface remnants
Soils with well developed B-horizon (firm)	B–C	Mainly on high benches and convex upper surfaces of old land forms
2.2 Yellowish brown gradational soils	F–F	Extensive on upper terrace in this zone
	D–F	Common on relatively young fans
2.3 Massive gradational soils	D–E	Widespread on concave valley fills
	C–D	On slope mantles and fans; also on well weathered in-situ bedrock
3. *Duplex Soils*		
3.1 Non-calcareous reddish duplex soils (earthy peds)	E–F	On the mid terrace in this zone
	D–E	On valley slopes and large, low-gradient fans
Non-calcareous reddish duplex soils (shiny peds)	B–D	Extensive on dissected older fan landscape of main valleys, on high terrace remnants and convex upper surfaces with well weathered bedrock
3.2 Calcareous reddish duplex	E–G	In the north-west on high terrace or valley plain, and prior stream ridges
3.3 Yellowish duplex soils with well developed B-horizon	E–G	On poorly drained high terrace
	D–E	On old, low-gradient fans
Yellowish duplex soils with moderate B-horizon development	D–E	Common on valley-fill and poorly drained terraces

mixing, they are often stratified, with beds of differing texture producing variations which do not fit the Northcote key. They are included in this general group because pedogenetic differentiation has not occurred, the main post-depositional development being the accumulation of organic matter in the surface 10 cm or more. Loams and finer textured soils, and particularly those inundated frequently usually have iron-oxide stains in root channels and other voids.

Surface textures vary considerably, reflecting the velocity of the water from which they were deposited. Thus, sandy loams tend to predominate in the upper reaches of the flood plain, loams tend to predominate in the middle reaches and clay loams and clays are the most widespread soils in the lower reaches, such as downstream from Albury on the Murray River and downstream from Wangaratta on the Ovens River.

Low levees of sandy loam or loamy sand may occur, mainly in the middle tracts of the main valleys, for example on the Kiewa at Tangambalanga and the Mitta Mitta at Noorongong.

These soils are usually referred to as alluvial soils (Rowe 1967, 1972), and Crouch (unpublished) has made two subdivisions, light alluvium and grey clays on alluvium. The group includes soils mapped as the Porepunkah, Myrtleford, and Wangaratta Series by Newell (1970).

1.2 *Sandy Loams*. Sandy loams occur on the coarse sandy sediment derived from granite, granodiorite and gneissic rocks. They are present both as shallow soils on the valley sides and as deeper soils on thick alluvial outwash fans and valley fills. Their occurrence is extensive in areas to the east and northeast of Albury, and to a lesser extent to the south of the Murray in the Thologolong area. They are also common in the broad basin-like valleys at the foot of the Barambogie — Mt. Pilot uplands and the Warby Ranges. Older clays may be found at depth.

The texture profile is typically uniform, but may tend towards gradational. Because of the dominance of coarse siliceous sand in the profile, textures are predominantly sandy and where a slight increase in clay has occurred, it may not be apparent in field texturing.

A typical sandy loam would have a greyish brown sandy loam A-horizon with only weakly developed structure. The A2-horizon would be of similar texture but bleached and lacking in structure. The gradual change to the pale brown or mottled yellowish brown B-horizon may occur at depths from 25 to 50 cm. The texture may vary from sandy loam to clayey sand, and coarse weakly developed structure may be apparent, although apedal B-horizons are more usual.

These soils are of low fertility and have low water

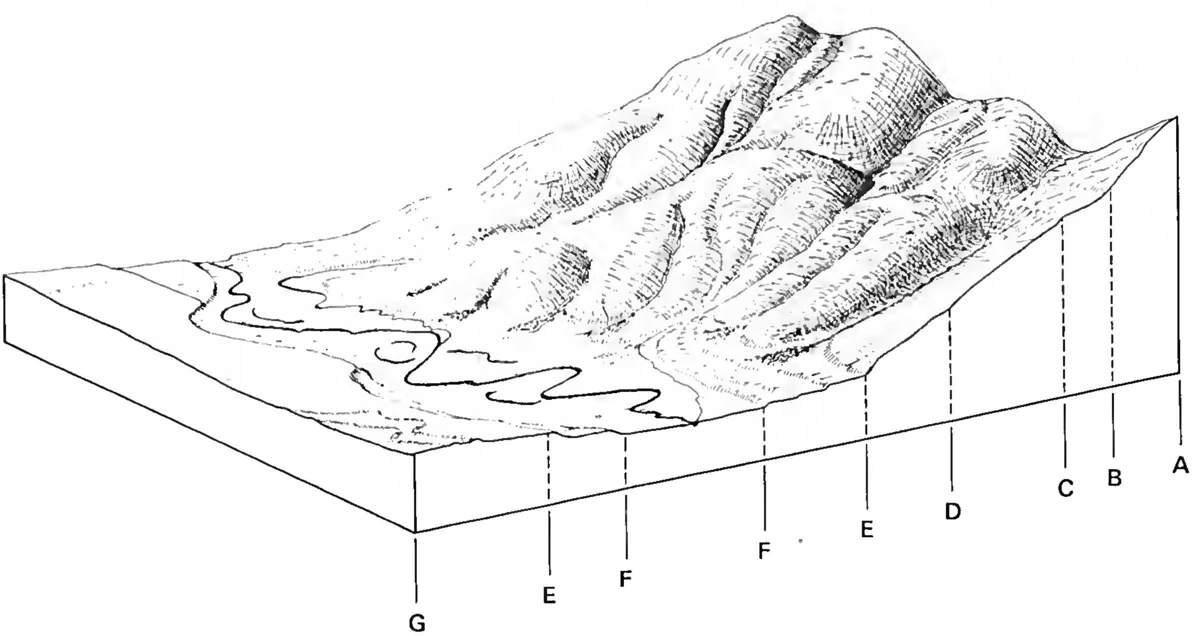

FIG. 3 — Generalised landscape diagram showing soil-geomorphic zones. A—B, steep valley side; B—C, valley side bench; C—D, sloping valley flank; D—E, alluvial fans-piedmont; E—F, terraces; F—F, flood plain; E—G, high terrace, valley-plain; including prior stream relicts.

holding capacity. They tend to be highly dispersible and set hard when dry. Deep gullies are common in them, both in natural drainage lines and where drainage is concentrated by earthworks.

1.3 *Grey and Brown Clays*. Soils of this group are dominant in swampy areas to the west of Albury and on the plains around Howlong and Rutherglen. They extend into the lower Ovens valley around Boorhaman and Peechelba East where they are associated with the prior-stream system on the extensive valley plain.

The grey and brown clays have a silty clay A-horizon which has a moderate crumb to subangular blocky structure. The colour becomes yellower or greyer and the clay becomes heavier with depth. Structure in the B-horizon is well developed blocky to subangular blocky and aggregates up to 10 to 15 cm across are common. Free lime is usually present in the subsoil.

These soils commonly have gilgai micro-relief. Although relatively fertile, they are not usually used for cropping because of seasonal water-logging. The clays have high shrink-swell capacity and surface cracking occurs as the soils dry out. The group has been described by Crouch and Junor (1976).

1.4 *Brown Loams*. These occur on terrace remnants just above normal flood levels or on higher parts of the flood plain, particularly in the middle to upper reaches of the main streams. They are well represented in the Ovens and Buffalo River valleys above Myrtleford and in the Kiewa valley around Tawonga and Dederang.

They are dark grey brown to very dark brown and highly sttructured in the surface 15 to 30 cm, but the structure declines and the colour pales with increasing depth. River gravel is usually present within a metre of the surface in the upper valleys, but deeper soils occur in lower reaches. In these latter areas the surface soil is greyer and iron oxide straining of root channels is usual; there may also be subsoil gleying. This form is more common in the lower reaches such as in the Kiewa valley at Bonegilla. Soils included in this group have been described as alluvial brown earths and meadow soils (Rowe 1967). The Ovens Series of Newell (1970) is included. The brown loams are moderately fertile soils which are used for summer crops including tobacco.

2. Gradational Soils

2.1 *Reddish Gradational Soils*. Two main groups with reddish gradational profiles can be recognised.

2.1.1. *Soils with minimal B-horizon*. Soils of this group occur on remnants of a terrace above the reach of normal flooding and on alluvial fans which may overlie older fans. These fans sometimes grade down to the terrace surface. The distribution is very discontinuous. The group is well represented around Whorouly, Porepunkah and Bright on terraces and fans, and in the Kiewa valley.

A characteristic profile would have a dark brown sandy loam to fine sandy loam at the surface, gradually changing through yellowish red sandy loam to reddish brown or strong brown sandy clay loam at about 50 cm. Below a weakly developed colour and texture B-horizon about 25 cm thick, the texture grades back to sandy loam.

In upper valley areas such as at Tawonga in the Kiewa valley, river gravel underlies the soil at about 1-1½ m. The structure is only weakly developed in both the A- and B-horizons.

The soils are relatively fertile and are used for pasture and for summer crops, as water for irrigation is usually available from nearby streams or from groundwater. In the Upper Ovens and Buffalo valleys these soils are used for tobacco growing. They have been recognized by Rowe (1972) as reddish gradational soils on alluvium, and the Merriang and Eurobin Series and two un-named series mapped by Newell (1970) are included.

2.1.2. *Soils with well developed B-horizon*. Two forms of reddish gradational soils with well developed B-horizons can be recognized. In one, the B-horizon is friable and only moderately structured with earthy ped fabric. In the other the B-horizon is strongly structured, peds have smooth faces and moist consistency is firm.

In general, soils of this group have a dark brown loamy A1-horizon over a yellowish red or reddish brown loam to clay loam A2-horizon which merges into the dark red or reddish brown light clay B-horizon. The A-horizon is about 20 cm thick and is moderately structured at the surface but weakly structured to apedal in the A2-horizon.

In the upper valleys, the soils with friable light clay B-horizons occur on older fans and upper terraces, and are common on the steeper slopes such as on the dissected old land surface which has been mapped as the Yackandandah land system (Rowe 1972). They are well represented in the upper Kiewa valley around Tawonga and in the upper Mitta Mitta valley south of Eskdale.

The form with firm B-horizon clays occurs on the gently sloping upper surfaces of the oldest fans and old surfaces such as the Stanley plateau and in the Yackandandah land system. In both forms, the depth of the profile may be in excess of 2 m and is

largely influenced by the thickness of the body of sediment or the depth of rock weathering. They are acid to very acid soils and of moderate to low fertility. The two forms have been described by Rowe (1972) but both are included in the amphipodsol group of Rowe (1967).

2.2 *Yellowish Brown Gradational Soils.* These are the predominant soils on what is usually the lowest extensive terrace in the Kiewa and Ovens valleys. They are particularly well represented around Wangaratta. Typically, they have a dark greyish brown or dark brown fine sandy loam to fine sandy clay loam A-horizon, and a slightly heavier textured, yellowish brown B-horizon. There may be a slightly bleached A2-horizon and there is usually weak 1 cm subangular blocky structure in the B-horizon. The maximum development of colour, texture and structure in the B-horizon occurs between about 40 to 80 cm, below which pedogenetic development declines.

They are moderately fertile soils and have an acid to weakly alkaline reaction trend. They are used for pastures and in some areas for summer crops, as water for irrigation is usually readily available.

2.3 *Massive Gradational Soils.* The most extensive areas of these soils in the valley landscape are on concave surfaces of valley fills between low convex slopes of older fans and low hills. Where stream incision has occurred these areas appear as terraces. These soils are also common on fans at the base of the steeper hills and in the slope mantles which may be of colluvial material or in-situ well-weathered rock.

A typical profile is not readily defined, as the group includes a range of rather variable soils, but all have in common a gradual increase in texture from loam or sandy loam in the A-horizon to clay loam, sandy clay loam or sandy light clay in the B-horizon, and except for the surface few cm which have a moderate structure, they are massive and set hard when dry. Colours range from dark greyish brown in the A1-horizon, through yellowish brown or pale brown in the A2-horizon to brown, yellowish brown or yellowish red in the B-horizon. The colour and texture changes are gradual but may not coincide. Gleyed profiles are common and ironstone concretions are also common in profiles with impeded drainage.

They are of relatively low fertility and moderately acid throughout, and are highly erodible. It is possible that these soils are the gradational form of the sandy loams, the latter being associated with coarser textured parent materials. The lepto-podzols of Rowe (1967) and the massive reddish and brownish gradational soils (Rowe 1972) are included in this group.

3. Duplex Soils

3.1 *Non-calcareous Reddish Duplex Soils.* These are the most widespread soils of the valley slopes and older terraces and fans in the lower valleys of the Mitta Mitta and Kiewa Rivers and the mid-valley tract of the Ovens from about Everton south to Bright. Around Albury they occupy the low ridge crests and bench situations on the higher hills. They are formed on a variety of parent materials but in the valley landscapes most usually on colluvium and alluvium.

Two main forms are readily recognised. One has earthy ped fabric and only moderately well developed structure in the B-horizon; the other has smooth ped fabric and strong fine pedality in the B-horizon. The former occurs on the terrace remnant just below the extensive high terrace-valley plain in the Ovens valley and on alluvial fans and valley fills (of presumably similar age) in the landscape. Those with the more strongly developed B-horizon are common on older land forms and are often found to have stone lines in the A-horizons or at the A-B boundary. Pedal red clay, similar to that of this later form, is often found as a truncated relict, buried under massive gradational soils or other weakly differentiated soils.

The most characteristic feature of the group, which is shared by both forms, is the contrast in colour and texture between the A and B horizons. Surface soils are typically dark greyish brown loam to sandy loam with a paler, often well bleached A2-horizon. The B-horizons are reddish brown, yellowish red or red clay. Mottled reddish brown and yellowish red B-horizons also occur.

These are all acid soils, although in some the reaction trend is towards neutral in the B-horizon. They are generally only moderately fertile and would show good responses to superphosphate.

The red podzolic soils (Rowe 1967, 1972, Crouch & Junor 1976) and the Randelong and Buffalo Series of Newell (1970) are included in the group.

3.2 *Calcareous Reddish Duplex Soils.* These occur in the north west of the area where they are relatively widespread: for example around Howlong and to the north of Wangaratta. They are found on old alluvium which forms a high terrace adjacent to the trunk streams, or on ridges of the prior-stream systems in these areas.

Soils of this group have a dark reddish brown loam or fine sandy loam A1-horizon which may be apedal and hard-setting or weakly structured, and a paler or bleached A2-horizon. There is an abrupt

change at about 15 to 30 cm to a red, reddish brown or yellow red clay B-horizon which has well developed subangular-blocky to blocky structure. Free lime occurs in the B-horizon. These soils are usually quite deep. The group includes the red brown earths and solonized red brown earths of Crouch and Junor (1976) and the Tara Series of Newell (1970).

3.3 *Yellowish Duplex Soils*. These soils occur generally in areas where drainage is impeded. Two main forms are recognized. In both the characterizing contrast between the A- and B-horizons is usually from loam, sandy loam or silty clay loam to medium to heavy clay. The colours vary from dark greyish brown in the A1-horizon through a paler, usually well bleached A2-horizon to the yellowish brown to olive brown whole coloured or mottled B-horizon. The A-horizons typically lack structure and are hard setting, but the B-horizons have moderate to well developed blocky to sub-angular blocky structure.

The main occurrences of the more extensive form of yellowish duplex soils are on old alluvium which forms the poorly drained extensive high terrace — valley plains to the north and west of Albury, around Bandiana — Bonegilla and around Wangaratta. They have a relatively thick well developed reddish yellow B-horizon with a distinct contrast between the upper and lower parts. The lower B-horizon has abundant soft ironstone segregations and the zone between the two parts may be somewhat bleached and have pisolitic ironstone. This soil is regarded by van Dijk and Rowe (in preparation) as a valuable soil-stratigraphic marker which typifies the Mudgeegonga pedo-morpholith.

In general, surface pH is acid but subsoil reactions are commonly less acid to around neutral. The group is considered to be of low to moderate fertility and suffers from impeded drainage.

The other less widespread form has a shallower profile and is found mainly on younger valley fills. It has a less well structured B-horizon and occasionally free lime is present in the lower B-horizon.

The yellow duplex soils with acid subsoils and those with alkaline subsoils (Rowe 1972) and the yellow solonetzic soils of Crouch and Junor (1976) are included in this group.

CONCLUSIONS

The area described is the transition zone between the Eastern Highlands and the Riverine Plain to the west. Massive dissection of old landscapes, extensive surface stripping of valley slopes and sedimentation of valley bottoms have all occurred within this area in the past. In more recent times the magnitude of the erosion and deposition have waned, but their effects are widespread.

Factors which have influenced the relative proportions of the surficial bodies of differing age, and therefore of the soils, include slope angle and length, configuration of the slopes, position in relation to downcutting or aggrading drainage systems, the nature of the rock and the depth of weathering, the climate, and probably even some element of chance. This means that although some generalizations can be made about the distribution of the main soil groups, description of the detailed patterns is more difficult, and in many situations it is possible to find soils of several ages associated in a more finely detailed version of the regional pattern.

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SOILS AND LAND USE OF THE RIVER MURRAY VALLEY IN SOUTH AUSTRALIA

By P. J. COLE*

ABSTRACT: The Murray Valley in South Australia is divided into 3 Tracts: (1) The swamps (once permanently flooded) which occupy the first 90 km of the narrow river valley that extends some 430 km upstream from the mouth, (2) The predominantly low terrace soils of the narrow river valley upstream from the swamps to Overland Corner, and (3) The high and low terrace soils of the wide river valley from Overland Corner to the Victorian border.

The heavy clay soils of reclaimed swamps of Tract 1 are high in organic matter, and while the level of irrigation management is low, they have remained productive for 80 years of irrigation. The low terrace soils of Tract 2 are saline grey clays with poor physical properties and are subject to flooding; agricultural use is limited. In Tract 3, about 15% of the area is high terrace, which has clay soils with sand layers at depth and at the surface; the horticultural areas of Renmark, Cobdogla and part of Berri are established here. The remaining soils of this Tract, mainly low terrace or dissected areas, are generally used for dryland agricultural or recreational uses.

Irrigation development in the Murray Valley in South Australia has been a consequence of low lift pumping of irrigation water rather than the suitability of soils for development.

INTRODUCTION

The River Murray in South Australia is some 700 km long. It includes Lake Alexandrina which extends about 60 km upstream from the mouth near Goolwa to Wellington. Taylor and Poole (1931) described the river valley in South Australia in the following way: 'The immediate floodplain of the River Murray passes through a series of gradual transitions from red gum and polygonum flats fringed with box trees . . . to barer, low lying flats subject to more frequent flooding, and finally to the permanent swamps of the lower reaches.' This description indicates the three distinct Tracts (Fig. 1) which reflect both the geological strata into which the river has incised, and the proximity to the mouth.

From Wellington to Overland Corner, 430 km from the mouth, an ancestral river, probably during the mid-Pleistocene period, cut a channel 60 m deep in the Morgan — Mannum Limestone (Firman 1973). This channel has subsequently been infilled with about 30 m of sediments (Recent deposits known as the Monoman and Coonambidgal Formations) resulting in a present valley floor 30 m below the surrounding country. The river valley is narrow, 1 to 2 km wide, often steepsided (Pl. 14, above) and the river is characterized by long, straight reaches. For the first 90 km above Wellington, permanent swamps once continuously flanked either side or both sides of the river (Pl. 14, below). This stretch of river is defined as River Tract 1. River Tract 2 occurs beyond the permanent swamps to Overland Corner (the bare, low lying flats of Taylor and Poole 1931).

Upstream from Overland Corner to the border, the river is incised in easily erodible Loxton and Parilla Sands of Pliocene age. Consequently, the river valley (River Tract 3) is wide (4 — 9 km), the banks not steeply sloping except where the river is actively eroding, and the river meanders. The valley is of similar depth to the other River Tracts. Schematic cross-sections of the three River Tracts are shown in Fig. 2.

The river valley has been used for agriculture since settlement: the earliest use was for grazing and as a stock route. Intensive use commenced with the irrigation scheme of the Chaffey brothers at Renmark in 1887, followed by village settlements at Waikerie, Lyrup, Pyap and elsewhere. In 1900, draining of the permanent swamps of River Tract 1 commenced, and extensive development for irrigation occurred all along the river valley for the

* South Australian Department of Agriculture & Fisheries, P.O. Box 411, Loxton, South Australia 5333.

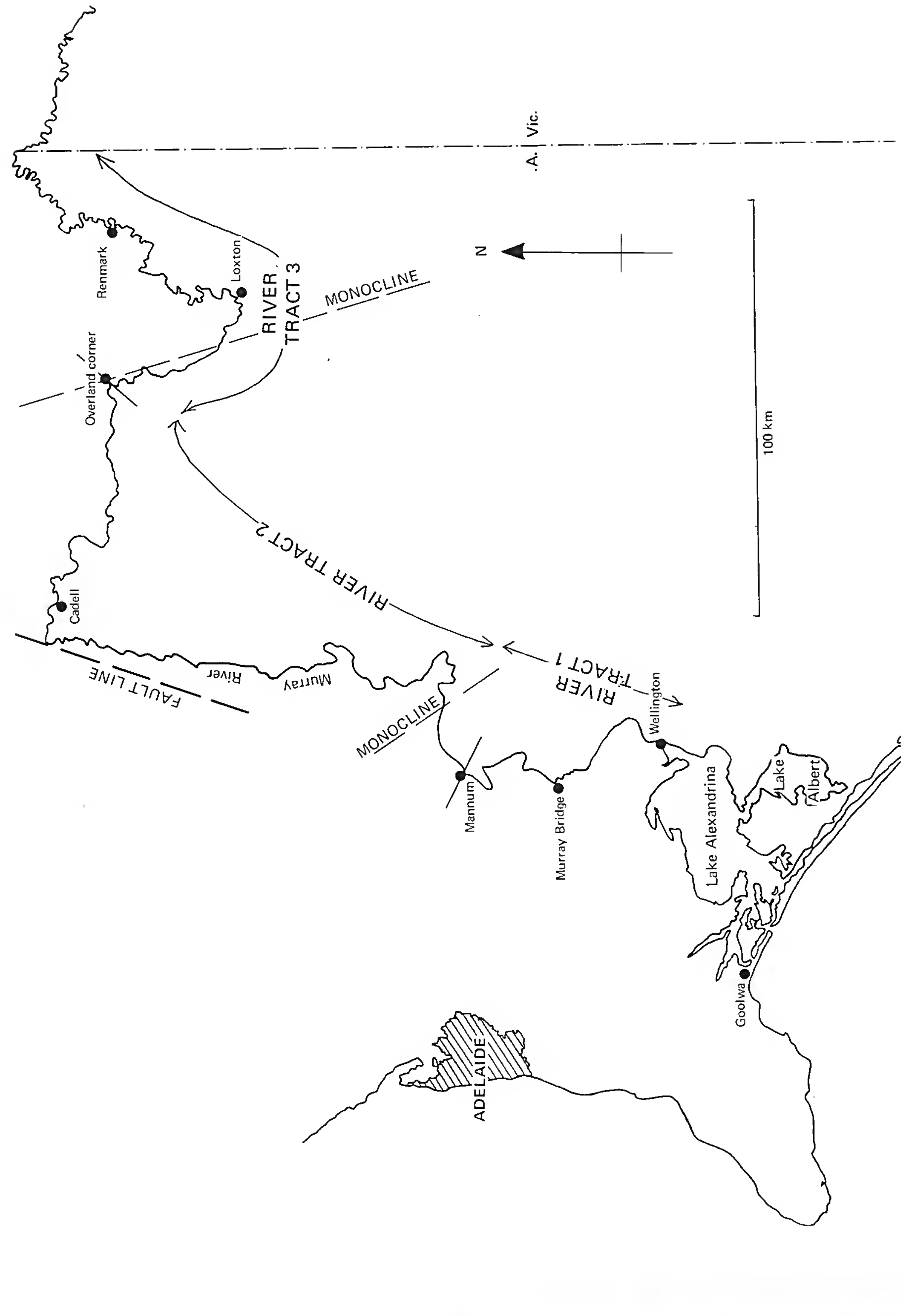
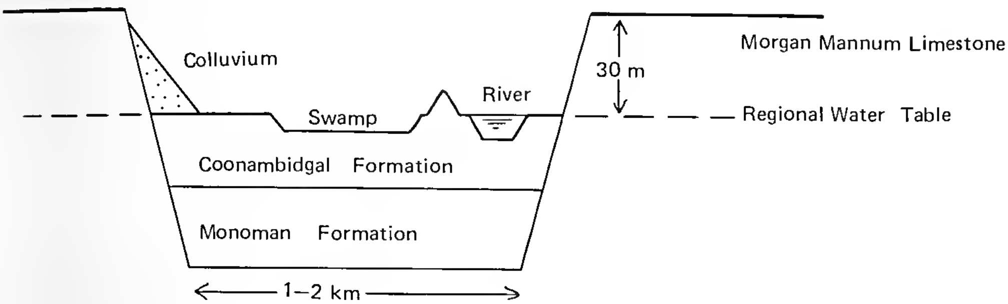
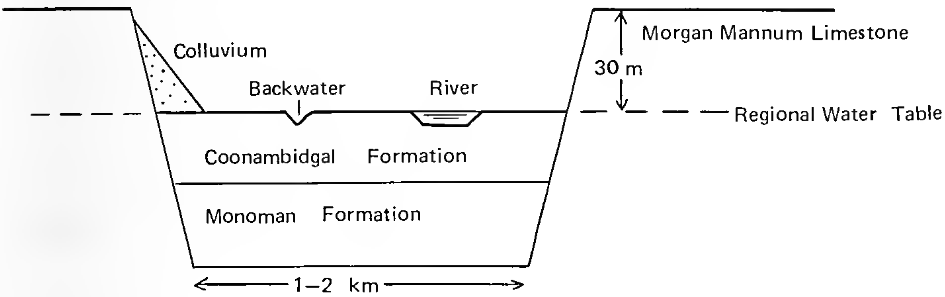


FIG. 1 — Location of River Tracts in South Australia.

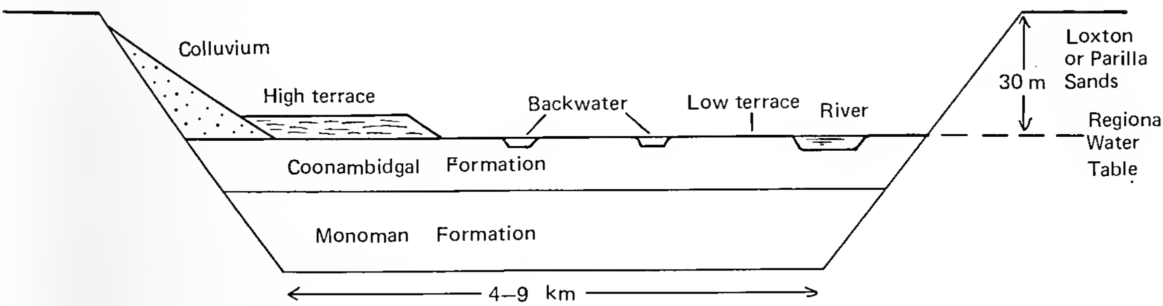
Schematic Cross-Section, River Tract 1



Schematic Cross-Section, River Tract 2



Schematic Cross-Section, River Tract 3



(adapted after Potter et al 1973)

FIG. 2 — Schematic cross-sections of River Tracts. Adapted after Potter *et al.* 1973.

next two decades. Renewed development and expansion of irrigation occurred after 1945. Of the 35,000 ha of irrigation along the River Murray in South Australia, over 10,000 ha of irrigation are within the valley itself, including about 5,000 ha of reclaimed swamp soils. The remaining 25,000 ha of irrigation are on highland soils adjacent to the river valley; these soils are not described in this paper.

Detailed soil descriptions were undertaken along the river valley in the late 1920's and 1930's by CSIRO (Taylor & Poole 1931, Marshall & Hooper 1935, and others). There has been little descriptive work since then. At the same time there has been a change of emphasis from description of

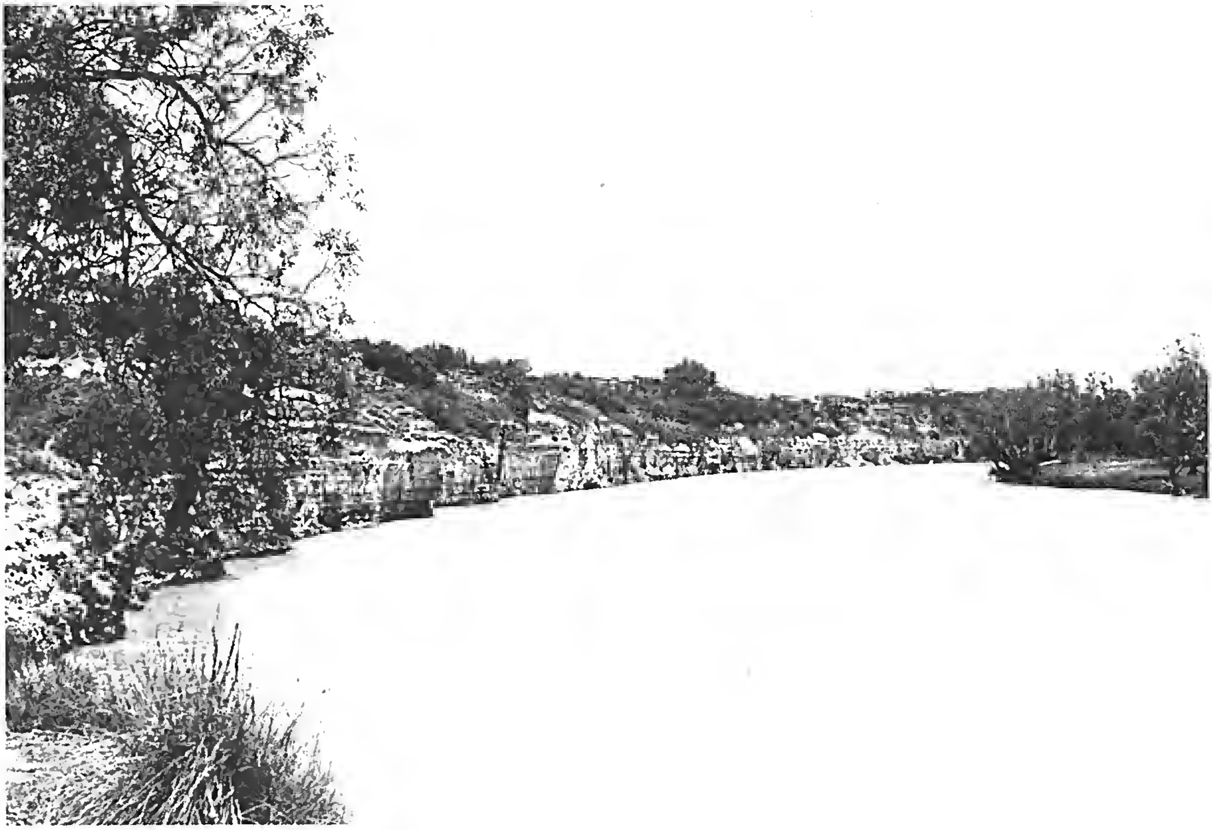


PLATE 14 *Above*, Steep sided river valley of Tracts 1 and 2. *Below*, Permanent swamp, River Tract 1.

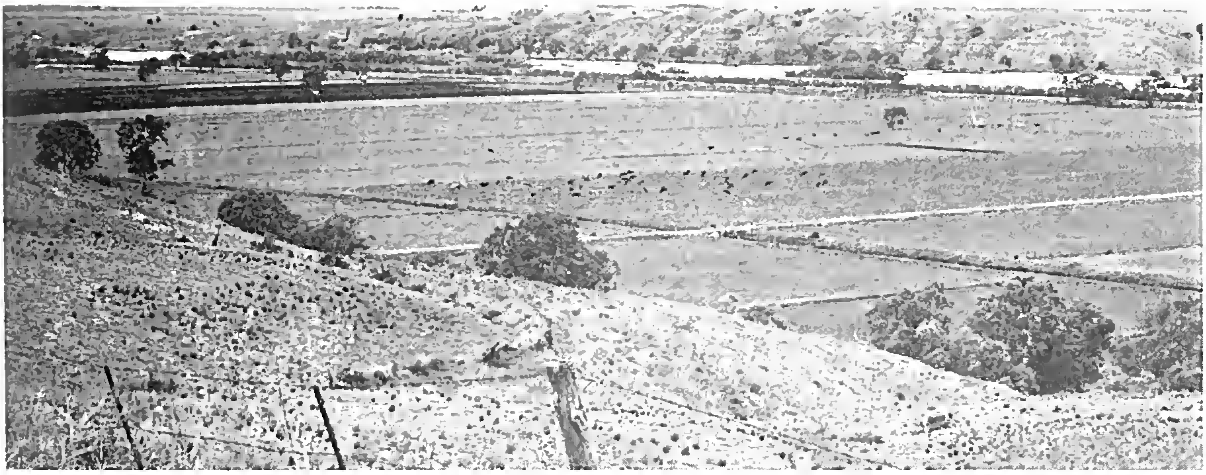


PLATE 15 *Above*, Reclaimed swamp, River Tract 1. *Below*, Salinised low terrace soil at Renmark (River Tract 3).

soil types to that of land units (Potter *et. al.* 1973). Much of the river valley has been described, if not mapped, in this way in recent years.

SOILS OF RIVER TRACT 1

Today, River Tract 1, is mostly a continuous series of drained swamps protected from flooding by levee banks (Pl. 15, above). Soil mapping of the swamps has indicated a diversity of soils of this Tract (e.g. Taylor & Poole 1931), as would be expected in an active riverine environment. Although it is a major task to map these soils in detail a number of soil types have been described.

The most common soil type of the swamps is a heavy clay soil (Fig. 3). The depth of the uppermost horizon of brown or black friable clay is variable but it is usually about 25 cm, and overlies at least 2 m of brown, black or grey clays. Peaty material and reed remains occur in some soils, with up to 35% of organic material in some of the peaty soils, although levels of about 10% are more common. Many of the soils of the swamps show evidence of having been burnt, which may have been expected from the high levels of organic material present.

Apart from the clayey soils of the swamps, both calcareous and sandy soils occur occasionally. The origin of the calcium carbonate and the sand is probably the country adjacent to the river valley, where the soils are calcareous and sandy, although some of the sands may have originated from reworked materials within the river valley. These swamp soils usually have a thin (less than 25 cm) heavy clay surface layer overlying bands of sands, calcareous clays and heavy clay. Gypsum may also be present in the lower horizons.

SOILS OF RIVER TRACTS 2 AND 3

The first soil description of these Tracts are those of Taylor and England (1929), Marshall and Hooper (1931, 1935) and Herriott and Johnston (1941). These surveys are typical of that era, with numerous soil types described (for example, nine for Renmark). The significance of land description was recognised, however, and the relationship of soil type to elevation above the river was observed.

The valley soils of Tracts 2 and 3 can be broadly classified according to the land description scheme of Potter *et al.* (1973). Four land unit facets were described for the river valley — high terraces, low terraces, dissected areas and sandhills or stranded sandbars. In River Tract 3 low terraces constitute 55% of the area and high terraces 15%, while in River Tract 2 there are fewer high terraces (estimated at only about 5% of the unit). The area of individual terraces in Tract 3 may be up to 400 ha whereas in Tract 2 areas of 100 ha are seldom exceeded.

The soils on the low terraces are medium to heavy clays, at least 2 m thick. They usually have poor physical properties, with low infiltration rates, low hydraulic conductivities and high bulk densities, and are often saline or underlain by saline water tables (Pl. 15, below) (Potter *et al.* 1973). Gypsum is commonly present in the profile. These soils were subject to frequent flooding prior to the construction of locks along the river to regulate flows, and are now flooded every 5–7 years.

High terrace soils have a few cm of fine sand at the surface, overlying sandy clay. Below about 1 m, sand layers (typically about 30 cm thick) occur. The soils may be saline. The physical properties of these soils are better than low terrace soils due to

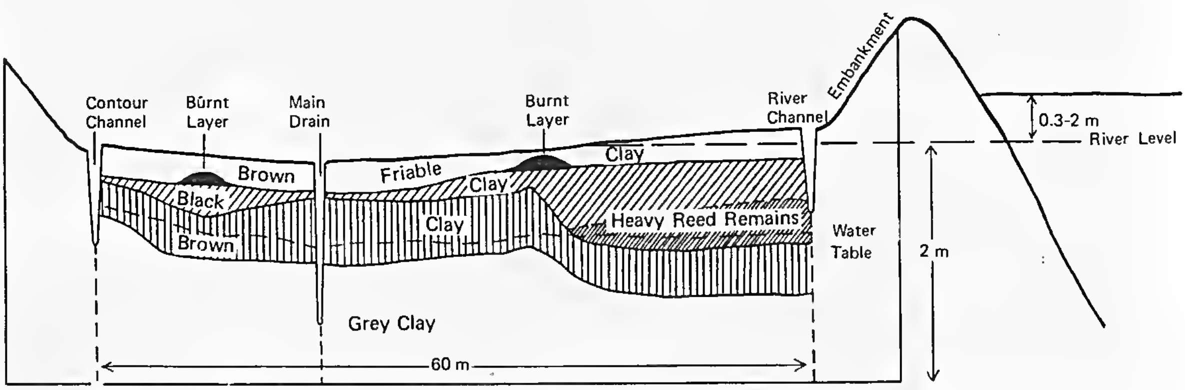


FIG. 3 — Cross-section of a typical swamp on the Lower Murray (River Tract 1). Re-drawn from Taylor and Poole (1931).

the lighter nature of the surface soil and the high hydraulic conductivity of the underlying layers.

The other two land unit facets of Potter *et al.* total less than 30% of the area of the valley floor. The soils of dissected areas are similar to soils of low terraces, whereas sandhills and stranded sandbars are deep (more than 2 m), medium to coarse-grained sands.

In both River Tracts 2 and 3 the valley sides may have soils developed on colluvial material. These soils are usually sandy, with carbonate in the profile and are usually free-draining if irrigated.

LAND USE

Some 10,000 ha of river valley soils are used for irrigated agriculture and horticulture. The swamp soils of River Tract 1 are flood irrigated for dairying and fat lamb production. Their high organic content results in a high natural fertility. Richardson and Gallus (1932) measured production from one swamp at 27,000 kg dry matter per ha per annum, although more recent work (reported by Cole 1971) measured yields of only about half this. Irrigation efficiency is poor and since the swamps are usually below river level, water tables are high and may be saline. Permanent drainage is essential, and reasons for declining agricultural production from the swamps are high water tables and poor irrigation management (Cole & Watson 1972). With the great risk of flood damage should levee banks be breached, there has been little incentive for farmers to improve

TABLE 1

LAND USE OF THE RIVER MURRAY VALLEY IN SOUTH AUSTRALIA

RIVER TRACT AND LAND UNIT FACET	SOIL	NATIVE VEGETATION	CURRENT LAND USE
RIVER TRACT 1			
Drained Swamp	Brown friable clay over grey, black or brown clays. Often high in organic matter. Variable.	Permanently flooded.	Irrigation: Improved pasture flood-irrigated for dairying, stock fattening, etc.
Undrained Swamp	—	—	Wildlife refuge, recreation.
RIVER TRACTS 2 AND 3			
High Terraces	More than 2 m of grey clay with layers of sand below 1 m; fine sand at surface. Sometimes saline. Up to 100 ha in area Tract 2, 400 ha Tract 3.	River box (*Eucalyptus largiflorens*). Old man saltbush (*Atriplex nummularia*)	Dryland: Grazing natural pastures. Irrigation: excellent for vines; Renmark, Cobdogla and Cadell irrigation areas are largely established on such terraces.
Low Terraces	More than 2 m of grey plastic clay, often saline. 10–120 ha in area. Poor physical properties.	River box (*Eucalyptus largiflorens*). *Lignum Luehlenbeckia cunninghamii*).	Dryland: Limited grazing of natural pastures. Irrigation: Occasionally flood-irrigated, usually for pastures. Flooded by the river every 5–7 years.
Dissected Areas	Similar to low terraces. Are natural levees and low lying areas in river bends with closely spaced dissections 2–3 m deep.	River box (*Eucalyptus largiflorens*). River red gum (*Eucalyptus camaldulensis*).	Dryland: Limited grazing of natural pastures. Excellent recreational and refuge areas.
Sandhills and Stranded Sandbars	More than 2 m of medium to coarse sand with little or no profile development. 2–20 ha in extent. Sandhills 6–10 m high.	River box (*Eucalyptus largiflorens*).	Rarely used for agriculture.

(Adapted from Potter *et al.* 1973, and Taylor and Poole, 1931.)

management practices. Undrained swamps are used for wildlife refuges and recreation.

With the predominantly low terrace soils of River Tract 2, intensive land use is restricted because of both the poor physical properties of the soil and the high risk of flooding. Some low terraces may be used for irrigation pastures, while high terraces at Cadell are used for irrigated horticultural plantings. Flood or furrow irrigation methods are used.

In River Tract 3, extensive areas of high terrace soils are used for horticultural production. Renmark, and parts of Berri and Cobdogla, are situated on high terraces. The main crop is vines, irrigated by furrow, with some highly productive areas (up to 50 t/ha) although yields are usually less than this. This yield can be compared with less than 20 t/ha which is more commonly achieved if low terrace soils are irrigated. The main advantages of the high terrace soils are the reduced risk of flooding, the absence of saline groundwaters in many areas, and the good physical properties of the soils. In times of major flooding even these soils may be covered, and changing river levels will cause fluctuations in water tables due to the permeable nature of the subsoil sand layers.

Non-agricultural uses of River Tracts 2 and 3 include recreation (e.g. a golf club at Renmark), and wildlife areas (including Games Reserves and one National Park). Some limited timber cutting is carried out in River Tract 3; grazing of stock on natural pasture is common all along the valley.

The land use of each land unit facet of the Murray Valley in South Australia is summarized in Table 1. That some soils are used for irrigated agriculture and horticulture at all is more an historical consequence of low-lift pumping of irrigation water, the only method available during development 80 years ago, than to the suitability of the soils for intensive agricultural use.

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17

SILVICULTURE OF THE RIVER RED GUM FORESTS OF THE CENTRAL MURRAY FLOOD PLAIN

By B. D. DEXTER*

ABSTRACT: River red gum, *Eucalyptus camaldulensis* Dehn, occurs in all the mainland States of Australia but its most extensive development is over some 60,000 ha on the flood plain of the Murray River in the region bounded by Tocumwal, Echuca and Deniliquin. Here the forests are usually flooded in winter and spring and form part of a natural flood control reservoir of some 4.1 million Ml capacity. This protects valuable agricultural land further down stream. The forests are also an important source of durable timber, and they have great value for wildlife habitat, recreation and grazing. For these reasons they are not likely to be converted to alternative land use. This paper discusses the silviculture of river red gum in the Barmah State Forest upstream of Echuca in northern Victoria. The red gum type comprises 24,440 ha of this forest.

Natural regeneration of the forest following utilization has been irregular in time and space. This has been due to variable flooding, unfavourable seed beds, inadequate seed supply, and soil drought induced by high evaporative losses and competing vegetation. Research has shown that useful germination occurs on unflooded areas in winter and early spring during periods of regular rainfall. Water temperatures during winter are generally unfavourable for germination on flooded sites, but germination is prolific following flood recession in spring. Soil moisture and seed-bed conditions are the main determinants of seedling establishment, although prolonged flooding limits such establishment even when satisfactory seed-beds have been prepared. It is therefore advantageous to promote rapid seedling growth and so minimize deaths or severe flood injury. Flooding is however largely uncontrollable.

During drought periods red gum seedlings may be destroyed by rabbits, kangaroos, wild horses and cattle. When feed is abundant the adverse effect of all these animals is slight. Extensive grazing of cattle on regeneration areas keeps weeds that are competing with seedlings for moisture in check, and seedling mortality due to soil drought is much less than on ungrazed areas.

The objective of management is to maintain within the Barmah State Forest red gum stands of various stages of development, with associated wildlife and native vegetation, appropriately zoned for timber production, public recreation, wildlife habitat and grazing. Prescriptions have been developed which facilitate the regeneration of utilized forest to satisfy these requirements. This objective can be achieved only if the forest or a substantial part thereof is flooded at least every second year and during suitable seasons. However, in recent years, intensive river regulation has seriously reduced the extent and frequency of winter and spring flooding and caused unseasonal summer flooding in low lying areas. These problems must be overcome if the river red gum forests are to be conserved.

THE RIVER RED GUM FOREST TYPE

This is a general description of the red gum forests on the flood plains below Tocumwal with special reference to Barmah State Forest. Studies of the flooding and regeneration of river red gum reported were carried out in Barmah State Forest between 1961 and 1967 as a project of the Research Branch, Forests Commission, Victoria.

The principal species, *Eucalyptus camaldulensis* Dehn, is found in all the mainland States of Australia but its most extensive development occurs over some 60,000 ha on the flood plain of the Murray River in the region bounded by Tocumwal, Echuca and Deniliquin (Incoll 1946), (Fig. 2). Here mature trees range from less than 21 m to 46 m in height. River red gum forms pure

*Research Branch, Forests Commission of Victoria, State Public Offices, Melbourne, Victoria 3002.

stands on the lower ground of the riverain forests, where it receives regular flooding. On higher ground it grows in pure stands or in association with black box, *E. largiflorens* F.v.M.; grey box, *E. microcarpa*; Maiden or yellow box, *E. melliodora* A. Cunn.

The average annual rainfall of 250 — 450 mm in the Victorian riverain zone is too low for vigorous growth, and the forests rely on regular flooding to meet the moisture deficiency.

Jacobs (1955), in describing the growth habits of red gum, noted that seedlings are non-lignotuberous, but a swelling which contains many dormant buds develops near the base of the stem. New shoots may develop from this when seedlings are injured. Cut stumps also coppice vigorously, and in some instances roots form on boles of saplings and young trees below water level when flood waters remain for long periods.

Red gum has weak apical dominance and poor stem form, especially when open grown (Jacobs 1955). Dense clumps of regeneration occur and in general dominance is asserted slowly, especially on the poorer sites. The form of most saplings in these clumps is good, whereas open grown saplings frequently have a short bole and heavily branched crown.

Red gum is very fire sensitive and even low intensity fire may cause cambial injury. Also it is often attacked by a large variety of insects. In severe cases the entire crown may be destroyed, but in the absence of repeated attack the crowns recover by means of epicormic buds.

Red gum, together with grey box and red ironbark, *Eucalyptus sideroxylon* A. Cunn., are the most valuable heavy construction timbers in southeastern Australia. The timber is renowned for its durability and strength in structural works, being particularly suited in large sizes for wharves, bridges, beams and piles. The main wood

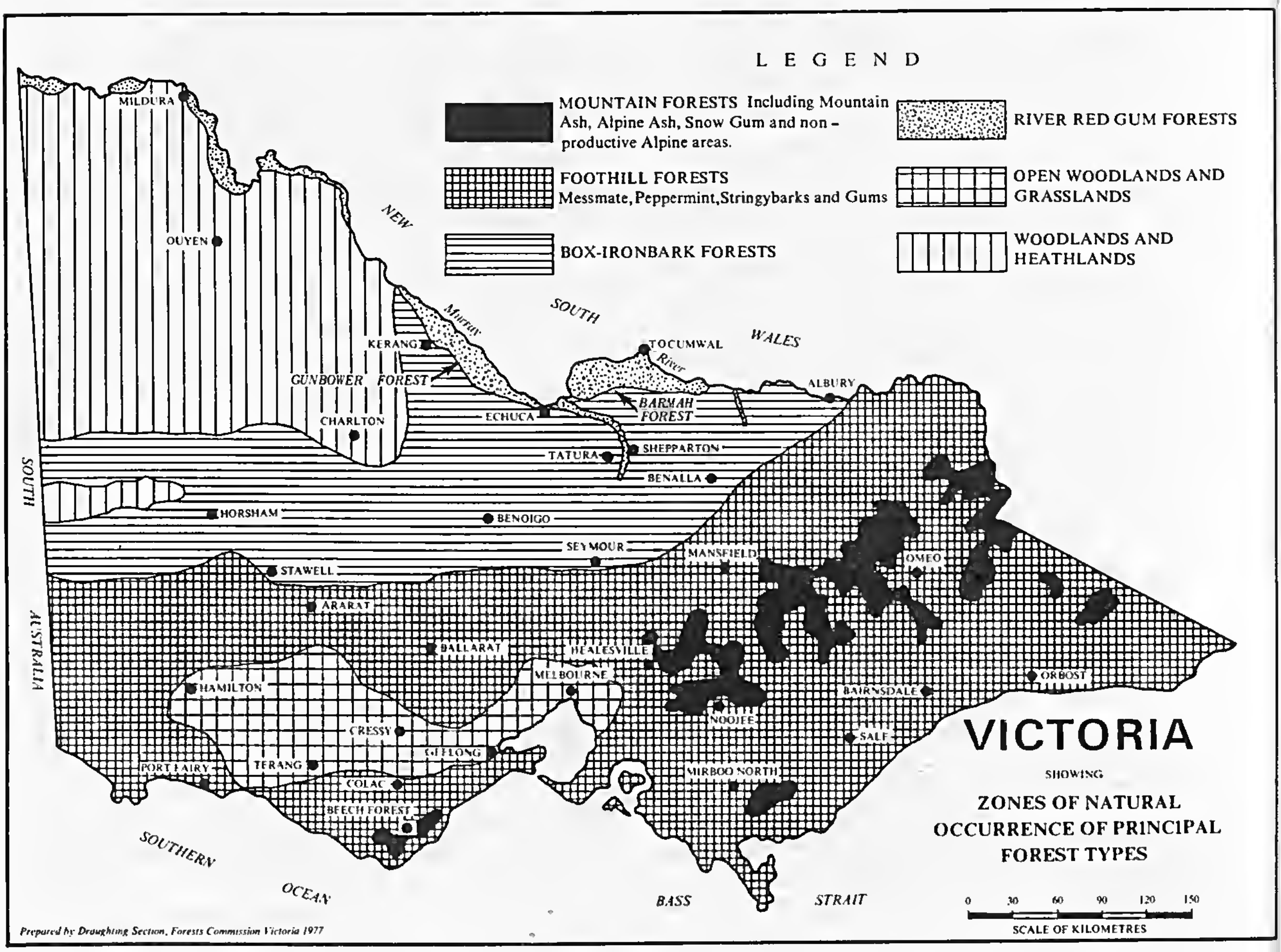

FIG. 1.

procurement operations conducted in river red gum forests at present are sawmilling and sleeper-cutting. The forests also have great value for wildlife habitats, recreation and grazing.

HISTORY OF REGENERATION IN BARMAH FOREST

Selective logging carried out during the past 100 years has resulted in the retention of large numbers of old trees of doubtful value, and defective smaller trees. These cuttings have on some occasions, produced scattered groups of regeneration. In addition to these stands of mixed age there are extensive areas of fairly even age resulting from widespread regeneration in the decade 1870 — 1880. On the basis of records of weather and flooding dating back to about 1860, Jacobs (1955) suggests that this decade constituted the first group of years favouring the extensive establishment of river red gum that occurred between the decline of the aboriginal hunter and his fires, and the increasing presence of sheep, cattle and rabbits.

Since the decade 1870 — 1880 there have been relatively few years during which widespread regeneration has established. Preliminary field observations, supported by flooding, rainfall and flowering records over the last 50 years, have indicated that fairly localized regeneration established in some areas during the periods 1903-04, 1917-18, 1934-35, 1937-38, 1957-58 and 1961-63. Otherwise, however, regeneration has been negligible.

THE PRESENT FOREST

The area under discussion is a flood plain of the Murray River ranging from 94.5 to 109.7 m above sea level (Harrison 1957). Internal elevations differ by only a metre or two with the exception of sand hills which may be up to 12 m above the general level. There are many water courses, swamps and grassy plains, which, together with the lower-lying timbered areas, are periodically flooded in winter and spring. Consequently, logging and other field operations are usually seasonal, often being restricted to six or seven months of the year.

The total area of Barmah State Forest is 28,900 ha. The red gum type comprises 24,440 ha and stands have been classified into three quality classes according to total height of mature trees. Quality I is greater than 30.5 m, Quality II 21 — 30.5 m and Quality III less than 21 m (Campbell 1962). Approximately 34% of the productive area is Quality I and 57% Quality II. The highest quality forest occurs on ground that receives regular flooding or which is thought to receive water from permanent streams via sandy aquifers.

Grazing has been carried out in the area for approximately 140 years. In the mid-nineteenth century several thousand sheep were grazed annually (Curr 1873) but since the turn of the century beasts have been mainly cattle. At present, this grazing is controlled by a system of agistment. In addition horses, kangaroos and rabbits are of considerable significance in the grazing balance of the forest.

The objective of management of this flood plain forest is to maintain the river red gum ecosystem. This includes the vegetation and wildlife associated with the grassy plains, watercourses, semi-permanent swamps, stands of Black and Yellow Box on higher ground and red gum stands of various stages of development. An important requirement of current management practice is the recognition of specific zones suited to various forest practices and the regeneration of utilized areas as soon as possible. The management objective can be achieved only if the forest or a substantial part thereof is flooded at least every second year during winter and spring. However, in recent years, intensive river regulation has seriously reduced the extent and frequency of such flooding and caused unseasonal summer flooding in low lying areas.

CLIMATE

Meteorological data indicative of conditions in the study area are given in Table 1. Temperature and rainfall were recorded at Echuca and evaporation was measured at Tatura (Fig. 1). Summer and early autumn are relatively hot. Days with a maximum temperature of 38°C or higher may occur 5 to 8 times each year between October and March, while days of 32°C or over occur 30 to 40 times a year. A frost-free period ranges from 7.5 to 8 months. Severe frosts are limited to a period of 8 weeks in June, July and August, and there are usually 6 — 8 each year.

The annual evaporation in the region is approximately 1375 mm. Because of these high evaporation losses and relatively little summer rain, survival and growth of young seedlings during this period depend to a large extent on availability of moisture stored in the sub-soil.

SOILS

Soils of the forest areas are periodically flooded and subjected to water logging, which results in pronounced mottling of sub-soil horizons. Clay is the predominant component of sub-soil horizons and compact layers below the surface hinder pene-

TABLE 1

TEMPERATURE, EVAPORATION AND RAINFALL FOR STATIONS IN THE VICINITY OF BARMAH FOREST.

Temperature and Rainfall are for Echuca, Evaporation is for Tatura.
Information taken from (Victorian) Central Planning Authority, Goulburn Region 1948 and data supplied by Tatura Horticultural Research Station.

	Temperature °C. (Base 58 yrs.)					*Evaporation (mm) (Base 14 yrs.)*	*Av. Rainfall (mm) (Base 30 yrs.)*
Month	*Mean Max.*	*Mean Min.*	*Mean*	*Highest*	*Lowest*		
January	30.72	15.28	23.00	46.11	4.44	234	21
February	30.77	15.38	23.10	45.00	5.56	184	33
March	27.28	13.17	20.22	41.94	2.94	148	26
April	22.00	9.56	15.83	35.00	−0.56	93	35
May	17.5	6.67	12.05	28.33	−2.22	55	39
June	14.06	5.06	9.56	22.50	−3.33	38	46
July	13.33	4.06	8.72	25.56	−5.00	33	44
August	15.11	5.06	10.06	25.89	−4.44	52	42
September	18.22	6.56	12.39	33.89	−2.22	80	40
October	22.28	8.94	15.56	37.78	−2.78	109	42
November	26.44	11.5	18.94	41.11	−1.11	156	27
December	29.22	13.83	21.56	44.44	1.67	209	30
Yearly mean	22.22	9.61	15.94			*Yearly Total* 1391	425

tration of water (Davies 1953). Nodules of calcium carbonate occur at various depths below the surface, indicating the depth of penetration of moisture down the profile (Leeper 1952, Butler 1958). The surface soil on areas that receive regular flooding is often silty and hard when dry.

Several profiles were excavated to depths of 1.8 to 2.4 m and although the findings may not apply generally to the forest, some significant features were noted. In some cases the sub-soil was stratified both with respect to composition and texture. Between 1.2 and 1.5 m there was a coarse sand layer several cm thick, and above and below this layer were predominantly clay fractions with a reddish-yellow mottling typical of iron compounds. In some instances there was 'ironstone gravel' in the profile, a feature of soils subject to periodic water-logging (Leeper 1952). Feagan (1947) and Davies (1953) reported similar findings from borings to explore underground water in riverain forests in New South Wales. A typical profile there showed clay layers overlying sand drifts followed by further clay layers.

There was no lateral percolation in those profiles which were uniform throughout. Such profiles excavated to about 1.2 m below the water level of a semi-permanent swamp and only 7.5 m away showed no evidence of lateral percolation after one week. However, there are hundreds of hectares of high quality forest located on a relatively narrow strip of river frontage which is not normally flooded. It is probable that these stands receive water via lateral percolation from the main stream. Davies (1953) found evidence of lateral percolation associated with stands adjacent to the Murray River. However, most borings indicated that there was no underground water within 9 m of the surface. Where underground water was present it was nearly alway confined to layers of sand or gravelly sand. Davies concluded that this water was associated with a prior stream bed under the present forest. How this water is replenished is a matter of speculation, expecially as the borings showed that the bulk of surface flooding penetrated only a metre or so through the clay. This was supported by ferric oxide staining in sands above the water table, but beneath heavy clays saturated down to about a metre below the surface, indicating that little downward passage of water had occurred beyond the saturated zone.

Extensive cracking of the surface soil is typical of most locations in the forest. Cracking commences with the onset of rapid drying conditions, and, by the end of summer, cracks of more than 25 mm in width have been traced to depths of 2 m. As little as 7 mm of summer rain may penetrate via these cracks to depths of more than 1.5 m. This source of soil moisture aids seedling establishment.

Further studies showed that the first one to two metres of soil profile are readily saturated even by floods of short duration. Penetration of water is facilitated by the deep cracks, and the sub-soil reaches field capacity at least to depths of 1.2 to 1.5 m. Even in the absence of flooding, the sub-soil is usually saturated in the young seedling root zone by winter rains, at least to 38 cms depth. However, soil in which moisture is replenished by winter rains commences to dry out again during late winter/early spring. By the time of flood recession in late spring/early summer, soil moisture tension in surface layers on unflooded areas may already be at wilting point and the soil has usually commenced to dry out in depth. This contrasts with the high moisture content of soils in flooded or very recently flooded areas.

GROUND FLORA

Moira grass *Pseudoraphis spinescens* (R.Br.) J. W. Vickery, forms the main ground cover in the forest and is also the dominant species on low-lying treeless plains. On heavy permeable soils on the fringes of the flood plain, needle rush, *Eleocharis acuta*, R.Br., forms the ground cover in low quality stands that are rarely flooded.

A list of some of the more common ground flora is given as Appendix 1, together with notes on their distribution within the forest.

FOREST GRAZING

The first record of organized grazing in Barmah forest dates back to the decade 1841 — 1851. During this period Edmund Curr (1883) a squatter, regularly drove sheep from winter runs in southern Victoria (then called the Port Phillip District) to the luxuriant summer pastures of moira grass that developed after winter/spring flooding. Curr obtained about 200 km^2 of open, grassy forest, occasionally broken by large patches of reed beds, south of the Murray river in the region of the Moira lakes. The size of Curr's flock of sheep varied from 5,000 — 10,000 head. In most years they were moved to the Moira country in November or December where they remained until frost browned the grass, generally in April. Sheep were then moved south to their winter run.

About 1848[1] the area became a 'Station' and even at this time grazing formed an essential part of the economy of the region. In 1864 a railway was established between Bendigo and Echuca. Utilization of red gum commenced on a limited scale and from about 1870 steam-powered sawmills were being operated to convert timber from the old, open forest into railway sleepers, paving blocks and other heavy construction timber. For the first time industry was being conducted at a level that would ultimately require the regeneration of the forest. In 1883 the first mention of rabbits was recorded on Stations[2] north of the Murray and no doubt they existed in the Moira region. In 1892 the Stations began serious attempts to eradicate the rabbit and since that time a constant campaign has been waged against the pest.

By about 1885, grazing of sheep in Barmah forest (known as the Barmah Common) gradually gave over to cattle and some horses. Local farm horses were frequently rested after the harvest period on the good summer feed in the forest. The forest was divided into two sections, each under a manager who was nominated by the stock owners to tend their animals on the Common. Gradually Government control was increased and in 1909 the then Forest Department appointed a herdsman to look after the stock.

Forest grazing has continued as an important local industry and allows farmers to carry considerable extra stock over the dry summer and autumn. In recent years about 2,000 head of cattle have had unrestricted grazing over 19,425 ha comprising the central and western sections of Barmah Forest. Usually about two thirds of the cattle are removed from the forest before winter because of the possibility of flooding reducing the area available for grazing.

As well as cattle, several mobs of wild horses roam the agistment area. These are the progeny of some of the former work horses and so far they have defied many attempts to remove all of them from the forest.

FLOODING IN RIVER RED GUM FORESTS

The Flood Regime of the Murray River

It is desirable to have some understanding of the Murray River system as a whole, as background to discussing flooding in the region within the triangle formed by Tocumwal, Echuca and Deniliquin (Fig. 2), where the river red gum forest type reaches its highest development.

The Murrumbidgee and Darling Rivers are the main tributaries of the Murray River in a catchment which occupies 107 million ha, covering approximately half of Victoria, three quarters of

[1] The following account was drawn from notes kept by settlers and kindly lent by many local residents, from newspapers and from records of the Forests Department.

[2] Notes taken on Tulla Station west of Deniliquin (Anon).

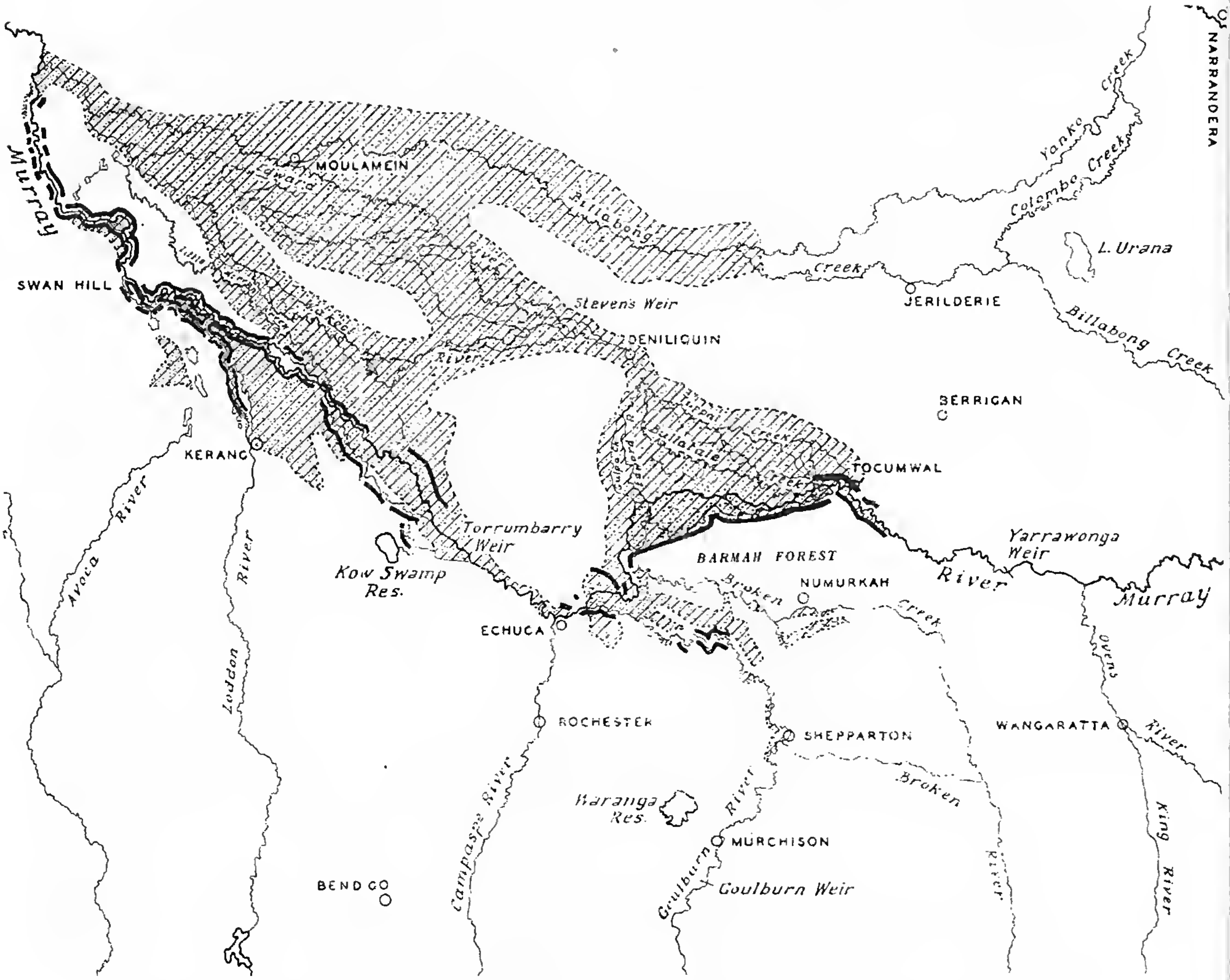

FIG. 2 — Flooding of the Murray River below Tocumwal showing existing levee banks (heavy black underlines) and flooded areas in 1956. (Courtesy of the River Murray Commission.)

New South Wales, one sixth of Queensland and, overall, about one seventh of the Australian continent (Ronalds 1950), (Fig. 3). Darling River catchments are principally located in Queensland and northern New South Wales where rainfall is generally due to summer monsoonal depressions. In contrast, Murray catchments above the Darling rely on winter precipitation for run-off. For this reason major floods in the two river systems rarely coincide, more especially as years of sustained high flow in the Darling system are mixed with very severe droughts. On occasions when peak floods do coincide, up to 607,000 ha are inundated in New South Wales and 101,000 ha in Victoria (Fig. 2). However, the flood mitigating capacity is not in proportion to these surface areas, the mean depth in Victoria being estimated at 1.13 m compared with 0.51 m in New South Wales (Harrison 1957). The total capacity of the natural flood control reservoir is approximately 4.1 million Ml. Victoria contributes about 1.1 million Ml which, in relation to the mean depth, represents approximately 13% of the total land area inundated and 25% of the total holding capacity for the region.

Floods in the region under discussion may occur at two periods of the year: from May to August from winter rains, and from September to November from spring rains and melting snow. Except in drought years at least minor flooding occurs in spring, whereas winter floods occur only in wet winters. Approximately 28,328 ha of Barmah Forest are inundated by overflows from the Murray River when the river height at Tocumwal approaches the critical flood stage of

6.1 m. This represents 30% of the land area inundated in the Victorian zone, and in relation to the mean depth, some 8% of the total holding capacity for the whole region.

Physiography of the Main Flood Basin

Below Tocumwal the western flowing Murray River between Deniliquin and Echuca was diverted south by the action of the Cadell Tilt Block, a ridge of land uplifted about 9 m. This block diverted the river south across the slope of the country to the limit of the faulting, where it again flows west after its junction with the Goulburn River. In low lying areas east of the Tilt Block the river developed a great number of anabranches and effluents, those on the east and south returning to the main stream in a relatively short distance and those to the west and north flowing into the Edward River offtake, returning to the main stream via the Edward and Wakool Rivers some 480 km westwards (Harrison, 1957), (Fig. 2). The significant feature is that overflows to Barmah Forest are much less important as far as wastage of potential irrigation water is concerned, as they soon return to the main stream near Barmah.

Criteria for Forest Flooding

The River Murray Commission and Water Conservation and Irrigation Commission, N.S.W. have provided data on stream flow for the Murray River at Tocumwal and, together with the State Rivers and Water Supply Commission, Victoria, have also provided data on diversion of Murray waters for irrigation in the Murray Basin. Stream

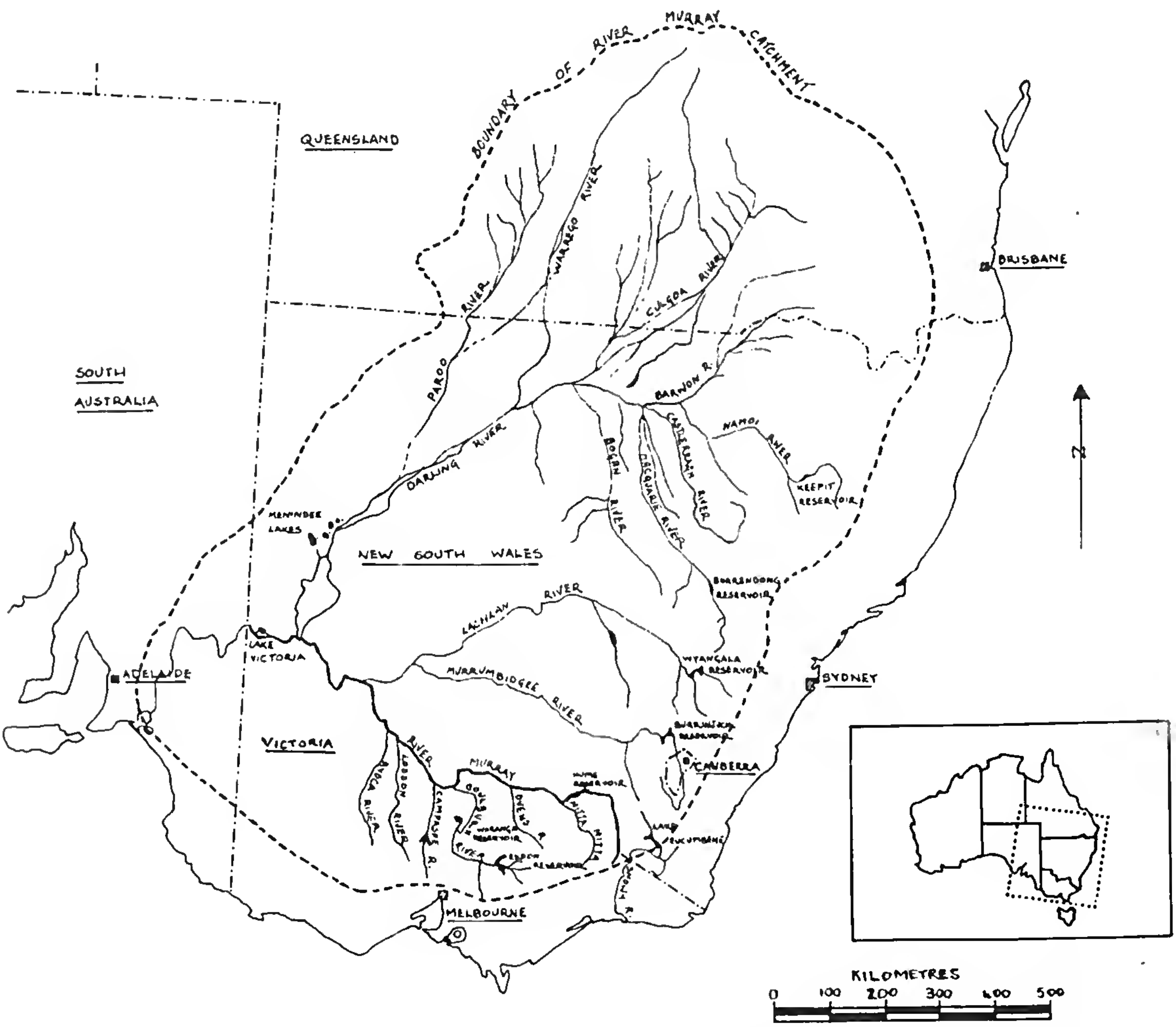

Fig. 3 — Catchment area of Murray River and tributaries. Catchment area 1,072,000 km^2. (Courtesy of the River Murray Commission.)

flow profiles showing the height of the Murray River at Tocumwal from May to December between 1886 and 1894, and profiles showing average monthly discharges in Ml per day at Tocumwal from May to December over the period 1895 — 1976 are set out in Appendix 2.

Examination of stream flow data and intensive investigations into forest flooding during 1961 — 1966 indicated that a flow of about 24,500 Ml (3.95 m) must be sustained at Tocumwal for four weeks to flood Barmah Forest (Dexter 1970). Gaugings at Tocumwal were chosen because of the availability of long term records and because there were no effluents or tributaries along the Murray between Tocumwal and forests on this section of the flood plain. Floods capable of inundating the whole of the productive forest area (24,440 ha) regardless of depth and duration were considered to provide an adequate watering.

Effect of River Regulation on Forest Flooding

Irrigation in the Murray Basin is dependent on water stored in Lake Hume (Fig. 3), which has a capacity of 3,083,705 Ml. A diversion weir at Yarrawonga, 233 river km below Hume Reservoir facilitates the distribution of water to irrigation schemes in the region.

Intensive development of irrigation schemes in the Murray Basin, particularly since 1934, has required a substantial increase in summer stream flow. Long term recordings taken at Tocumwal (State Rivers and Water Supply Commission) show that stream flow, for the months of December to May inclusive, has been increased by the release of stored water from about 20% of the average annual flow for 1895 — 1933, that is, before intensive river regulation for irrigation affected the natural flow, to about 30% for 1934 — 76.

The higher river levels in summer and autumn increased the volume of water entering Barmah Forest via effluents. This increased flow, together with periods of natural flooding led to some lower-lying areas of forest being more or less constantly inundated. These conditions inhibited the establishment of regeneration on these areas, killed some mature red gum stands, and caused deterioration of other stands over hundreds of hectares. Regulators were installed on major effluents between 1939 and 1959 to exclude water from forest areas during the irrigation season. The operation of regulators, which is under the direction of the River Murray Commission, is designed to exclude water from entering the forest except when an over-flow of the natural banks could occur. The volume of water released from the main stream is the minimum required to keep river flow within the natural banks.

Water is naturally excluded from regulated effluents along river banks bordering the flood plain forests until stream flow exceeds about 6,000 Ml per day at Tocumwal, and may be excluded at the discretion of irrigating authorities until the flow exceeds about 11,000 Ml per day. At this stage water is declared surplus and regulated effluents are usually opened to prevent over-topping of the natural banks along the flood plain and to minimise bank erosion. When sustained flows exceed about 18,000 Ml per day, control by regulated effluents is lost in both Victoria and New South Wales. Consequently, banks bordering the flood plain are overtopped and forest areas function as a natural flood control reservoir.

For several years some summer flows have exceeded 11,000 Ml per day but the regulators have been kept closed to avoid substantial losses of water for irrigation projects downstream. This situation, coupled with the cancellation of planned diversions of water due to local summer rain, has caused serious unseasonal flooding in some low lying areas of forest.

By arrangement with the River Murray Commission, regulated effluents are usually opened during winter months after Lake Victoria (Fig. 3) reaches near-full capacity. Flows less than 11,000 Ml per day are included because there are no further storages downstream to collect surplus winter flow. Lake Victoria was near full capacity when surplus water passed down the Murray River during the winters of 1961, 1962, 1963 and 1964 (Appendix 3). However, it did not reach full capacity by spring 1967 and regulators were kept closed. Data in Appendix 3 show that water could have been almost completely excluded from Barmah Forest during 1961-3 if regulators had been kept closed below a sustained flow of 11,000 Ml per day. With greater demands for water to satisfy the agricultural and urban requirements in the Murray Valley in Victoria, New South Wales, and in South Australia and the greater regulatory capacity afforded by the construction of Dartmouth Dam, it is likely that this situation will occur more frequently unless storages are filled early in the year.

Further to these effects, the regularity with which the whole of Barmah is flooded has declined with the advent of intensive river regulation. Based on the criteria that a flow of approximately 24,500 Ml must be sustained at Tocumwal for about four weeks to flood Barmah Forest adequately, the data

given in Appendix 2 show that the forest was watered in 40 out of 48 years between 1886 and 1933, the period before Hume Reservoir affected the natural flow. Since then the forest has been watered in only 26 out of 43 years. However, stream flow profiles illustrating estimated natural flows show that between 1934 and 1976 an adequate watering would have occurred on seven additional occasions, namely 1937, 1941, 1959, 1962, 1963, 1965 and 1968, if stream flow had not been intensively regulated via Hume Reservoir. Information on rainfall drawn from Hunt (1911), Watt (1937), and the Commonwealth Bureau of Meteorology records for the Murray River catchments above Tocumwal indicate that the decline in flooding has not been due to consistently low rainfall in the catchments. In fact it now appears likely that a full flooding will occur only in years when winter/spring rainfall is well above average. Furthermore, when floods do occur drainage of the low and middle level forests is sometimes delayed, water receding in summer rather than spring. This is because the Murray River below Tocumwal is more frequently above bankfull capacity later in the year compared to the pattern prior to regulation. It will be shown in later sections that summer flood recession may be harmful to red gum establishment.

THE PROBLEM OF REGENERATION

Following the 1944/45 drought there was a period of eight consecutive years when the forest was regularly flooded and seasons were thought to be generally conducive to widespread seedling establishment. However, little worthwhile regeneration was observed to survive beyond the first year. (For. Comm. Vic. 1961). By 1951 concern by the Forests Commission over the lack of regeneration led to the closure to cattle grazing of 6,475 ha in the eastern section of the forest. In addition, local officers established a series of plots, both fenced and unfenced, in the central and western sections and regular observations were carried out to follow the progress of regeneration. By 1960 it was apparent that few seedlings were becoming established in any of the wide variety of locations (For.Comm. Vic. 1961). The situation obviously required a more detailed study to examine all aspects of the regeneration problem.

Valuable leads into the problem were given by Jacobs (1955) who suggested that regeneration of these flood plain forests may be complex and that special conditions may be necessary to secure seedling establishment. Jacobs, over many years, identified several factors that could be responsible for the great variation in the success of regeneration. He considered that the problem was one of establishment and not of germination and supported this by noting such features as the copious amount of seed produced, the probability, because of periodic flooding, of fewer seed-robbing insects on the forest floor, and the many germinates that regularly appeared when moisture conditions were suitable. However, Jacobs found that few of these seedlings survived, probably because they were very sensitive to both drought and excessive flooding in the first two years. In relation to these factors the level and duration of flooding, which may vary markedly from year to year, can greatly influence the success of regeneration. Jacobs also noted that intensive grazing of seedlings, which can be eaten by rabbits, sheep, cattle and horses, can limit regeneration. Other factors suggested as being deleterious included the influence of bad local seasons and the dominance of veteran trees over many areas.

In 1961, cut-over sections of Barmah Forest were surveyed to assess stocking of regeneration and to appraise characteristics of site and environment that may influence survival and growth of regeneration. Extensive surveys showed that there was usually a prolific strike of seedlings throughout the forest in winter and spring following abundant seed-fall in the preceding summer and autumn. In most instances however, few of these seedlings persisted through summer. Intensive regeneration surveys of cut-over areas showed that usually less than 25% of milacre quadrats were stocked. However, it was notable that quadrats with at least half their area either as disturbed soil or ash bed were much more frequently stocked than quadrats with undisturbed surfaces.

In fact, the surveys indicated that sites favouring establishment of seedlings in average seasons were mainly disturbed, bare, or burnt areas at least 20 m distant from an overstorey tree. In some cases regeneration was confined within definite narrow elevational limits. Established seedlings had a very 'clumped' distribution and frequently occurred in dense thickets. This type of distribution may have been induced by the very specific site factors required for regeneration to establish. In addition, seed source on some areas surveyed was poorly distributed and inadequate.

A provisional standard of acceptable stocking of regeneration has been set at 50% by stocked milacres. Several factors have influenced the choice of such a high stocking standard for river red gum. A relatively dense stand is needed to produce trees with clean, straight boles. Open-grown trees have

short boles and are heavily branched. Fairly dense stocking in the sapling stage is also desirable because at no stage are the eucalypt saplings in competition with associated vegetation that could prevent development of strong laterals. The high frequency of poor form in sapling stands requires that crop trees be selected from a large initial population. In addition, saplings in well-stocked stands are much less susceptible to damage by animals than are open-grown saplings.

The surveys also indicated that the following factors may influence the establishment of a satisfactory density and distribution of regeneration:

1. Seed supply.
2. Incidence of flooding.
3. The time of flood recession, which depends to some extent on whether recession is by drainage or by evaporation, and on the elevation of the areas.
4. Seed bed type.
5. Availability of moisture in the sub-soil.
6. Distribution of summer rainfall.
7. Insects, domestic and other animals.
8. Duration and depth of flooding in the season following germination.

Studies of these factors have been previously described by Dexter (1967) and only a brief summary of the main findings is presented below.

REGENERATION OF RIVER RED GUM

Flowering and Seed Fall: River red gum flowers in most years from late spring to mid-summer but the intensity of flowering varies widely and unpredictably from year to year. About 45% of flowers through the full range from heavy to light flowerings fail to mature. This feature, together with the possibility of very high losses of seed to insects means that natural seed supply is sometimes insufficient for the regular establishment of seedlings.

Seed fall occurs throughout the year commencing about nine months after flowering ends. Free seed fall is least during winter and greatest in spring and summer. High seed fall in spring may have adaptive significance as floods usually recede during this period.

Germination and Seedling Mortality: Useful germination appears on unflooded areas only in winter and early spring and then only in those years when there are significant wet periods. On flooded areas water temperatures during winter are unfavourable for germination, but germination is prolific following flood recession in spring and early summer.

In non-flood years lethal cold temperatures may kill up to 25% of cotyledon-stage germinates growing in exposed situations, whereas germinates protected by surface cover may sustain less than 10% losses. Seedlings that survive the main frosty period are usually sufficiently advanced to withstand high soil surface temperatures. However, in drought years growth is slow and many cotyledon-stage germinates are killed through their hypocotyls being girdled by temperatures exceeding 65°C at the soil/air junction. Most deaths occur on ash bed and in grass where lethal high temperatures occur early in the growing season. In the absence of a suitable flood regime, soil drought is one of the major causes of seedling mortality. Unless seedlings are fast grown, as for example on ash bed and cultivated seed beds, or summer rains are well above average, soil drought may account for up to 94% loss of seedlings less than twelve months old.

Prolonged flooding is also a major cause of seedling deaths. When flooding is prolonged, seed is either destroyed or young germinates are killed by the hot conditions that usually prevail at the time of late flood recession (mid-summer). Flooding, particularly complete immersion for several months, is lethal to most seedlings less than 25 cm in height. Varying proportions ranging up to 95% of seedlings 50 to 60 cm in height may survive from four to six months inundation depending on the period of total and partial immersion. If flood recession is quick there are few additional deaths, but if recession is slow many of the partially immersed seedlings die. With respect to relatively short term flooding, seedlings can survive up to 14 weeks inundation, including a few weeks of complete immersion, with little ill effect. The only damage sustained is the shedding of the lower leaves of small seedlings.

Growth Habits and Survival of Seedlings: Young seedlings have characteristics which assist them in surviving periods of moisture stress in spring and summer. Woody stemmed seedlings at least up to 15 cm in height may shed all their leaves in times of prolonged moisture stress and recover via shoots from axillary buds when moisture becomes available again.

All classes of seedlings beyond the cotyledon-stage and at least up to 23 cm in height have an average root length/shoot length ratio of 4.5. Root systems of well developed seedlings therefore extend deep into the sub-soil where moisture is generally available for survival over summer.

Rapid early growth associated with receptive seed beds is important for seedling survival and establishment. For example, at age three to five months the average height of seedlings on deep ash bed and well cultivated surfaces is four to eight

times that of seedlings on hard, bare surfaces and grassed sites. On receptive seed beds, the root systems of these seedlings develop down to 20 — 50 cm below ground surface, that is, four to eight times the depth of root development on unreceptive seed beds. Moisture is usually available for seedling survival under receptive seed beds over summer, even in the absence of previous winter/spring flooding. Furthermore, initial rapid growth aids establishment, and big seedlings are least likely to be destroyed or badly injured by a period of flooding in the year following germination.

Influence of Trees and Ground Flora on Seedling Establishment: In the absence of flooding, winter rains can provide sufficient soil moisture for the establishment of river red gum seedlings provided ground vegetation and/or overstorey trees are not competing for this moisture. On sites colonized with annuals and perennial grasses, moisture is rapidly depleted early in the growing season. In the absence of competition seedling survival is some 20 to 30 times greater.

Similarly, the availability of moisture for seedling survival is greatly reduced within the zone of influence of trees. The zone appears to increase with lowering of site quality and may extend for up to 40 m around a mature tree. The severity and duration of moisture stress imposed by these agencies depends on the prevailing seasonal conditions and flooding.

Grazing: During prolonged dry periods when feed is scarce, heavy browsing by rabbits and kangaroos will destroy the majority of young red gum seedlings. Serious damage is usually localized to a few hectares. When feed is abundant, the effect of these animals is slight. Cattle and horses have a similar potential to destroy young seedlings but this rarely occurs under the present system of grazing under agistment in Barmah Forest. Likewise, under this system, grazing of cattle on regeneration areas is not detrimental to seedling establishment. In fact, cattle grazing on weeds, which would otherwise be in strong competition with young seedlings for moisture, results in seedling stocking remaining at a satisfactory level. Without the control of weed competition, seedling stocking may fall below requirements for effective regeneration.

SILVICULTURAL TECHNIQUES

Studies of the main requirements for seedling establishment have led to the development of procedures which greatly improve the chances of obtaining adequate regeneration. These are based on effectively distributing seed on to receptive seed beds. Seed beds are made receptive by removing grass and other vegetation, preparing the ground surface by slash burning and cultivation, and poisoning non-merchantable trees. Seed is provided by inducing seed fall from an adequate proportion of crop trees or by direct seeding. There are two main silvicultural techniques that are variously applicable to regenerating river red gum.

(1) Procedures Based on Direct Seeding

Clear felling followed by aerial seeding is the cheapest and most flexible technique. The major costs involved are in seed bed preparation, poisoning non-merchantable trees, collecting seed, and in aerial seeding. None of these operations is expensive. Sowing rates and time of sowing are determined on the bases of expected flooding and seed bed quality.

(2) Procedures Based on Natural Seed Supply

These procedures involve preparation of seed beds and inducement of seed fall during summer and autumn, then utilization of merchantable, and poisoning of non-merchantable trees. The required timing of each phase to suit such factors as seed maturation, and seed fall and germination reduces flexibility and increases costs. One of these techniques, clear felling in one stage, is applicable to lightly stocked areas that have been previously heavily cut-over. The second, clear felling in two stages, is applicable to areas which have been less heavily cut-over and on which most of the crop can be utilized.

The choice of the regenerative procedure will depend on the particular characteristics of the stand to be utilized: for example, availability of natural seed source, volume of merchantable material, size and location of coupe. Other constraints to be considered are the shortage of labour and the unpredictable seasons associated with red gum forestry. With the procedures tested, experience has indicated that two-stage cut techniques can become unmanageable, especially on coupes exceeding 20 ha, because of difficulties in adhering to the required timing of each phase of the operation. On the other hand, operations based on clear felling and direct seeding are much more flexible. Field trials of these techniques have regularly provided satisfactory stockings of regeneration.

MANAGEMENT

The objective of management of Barmah State Forest is to maintain the river red gum ecosystem with its variety of forest conditions, associated wildlife and native vegetation, so that it is capable of sustained use for timber production, public

recreation, wildlife habitat and grazing. An important requirement of current management practice is the recognition of specific zones suited to these various forest practices, and the regeneration of utilized areas as soon as possible. The objective can be achieved only if the forest, or a substantial part thereof, is flooded at least every second year and at suitable times of the year. However, regulation of river flows in the Murray catchment above Tocumwal is causing problems. It is reducing the frequency and extent of winter and spring flooding on the low-lying middle level areas of the Barmah Forest, and mostly eliminating floods on the higher red gum areas. Furthermore, when floods do occur, drainage of the low and middle level forests is being seriously delayed, water receding in summer rather than in spring. This is because the Murray River below Tocumwal is more frequently above bankfull capacity later in the year compared to the pattern prior to regulation. High levels in the river when water is being delivered from storages are also causing summer floodings. These occur at short notice when there are sudden cancellations in diversions for irrigation water.

These changes are having ill effects on the forest. The red gum in the low and middle levels needs winter or spring flooding. Without water at that time it is unable to make vigorous growth and becomes subject to serious attack by the seedling gum moth. Late drainage causes serious losses of crops of young seedlings and saplings, and spillovers from the high summer river levels accentuate the development of wet lands in low areas with death of trees, spread of reed beds and losses of grazing country.

Furthermore, these departures from the natural sequence of flooding also cause changes in waterfowl habitat. Duration and depth of flooding, and more particularly season of flooding, control the regeneration of ground flora which are important to the feeding and nesting requirements of these birds. Consequently, the reduction in the frequency and extent of winter and spring flooding, the late recession of water and unseasonal summer flooding, are factors of great concern.

With the construction of Dartmouth Dam the storage capacity in the Upper Murray has been increased by some 3.7 million Ml. The greatly increased regulatory capacity thus provided could further reduce winter flows above bankfull capacity in the central Murray flood plain. It could also seriously aggravate the summer flooding problems if high river flows are maintained for irrigation requirements.

Such problems must be overcome and a suitable watering regime developed in consultation with regulating authorities if the river red gum forests are to be conserved.

ACKNOWLEDGMENTS

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APPENDIX 1

SOME OF THE MORE COMMON GROUND FLORA FOUND IN BARMAH FOREST WITH NOTES ON THEIR DISTRIBUTION

Botanical Name	*Notes*
A. Monocotyledons	
Agrostis avenacea J.F. Gmel (Gramineae)	Rarely flooded areas; low site quality.
Anguillaria dioica R.Br (Liliaceae)	Species colonizing cultivated areas subjected to regular flooding.
Bromus macrostachys Desf. (Gramineae)	Rarely flooded areas; low site quality.
Danthonia duttoniana A.B. Cashmore (Gramineae)	Rarely flooded areas; low site quality.
Hordeum hystrix Roth (Gramineae)	Rarely flooded areas; low site quality.
Juncus subsecundus N.A.Wakefield (Juncaceae)	Low swampy areas.
Koeleria phleoides (Vill.) Pers. (Gramineae)	Rarely flooded areas; low site quality.
Lolium perenne L. (Gramineae)	Rarely flooded areas; low site quality.
Phalaris tuberosa var. *stenoptera* (Hack) Hitche (Gramineae)	Generally on high ground; rarely flooded.
B. Dicotyledons	
Acacia acinacea Lindl. (Leguminosae)	Box ridges, rarely flooded.
Alternanthera denticulata R.Br. (Amaranthaceae)	Colonizer of bare soil areas and ash beds; site quality 1-3.
Cardamine hirsuta (L) (Crûciferae)	Rarely flooded areas; low site quality.
Centipeda minima (L) A.Br. et Aschers (Compositae)	Unflooded areas or areas subjected to irregular flooding.
Centipeda cunninghamii (D.C.) A. Br. et Aschers (Compositae)	Colonizer of bare soil areas; site quality 1-3.
Cotula bipinnata Thurb (Compositae)	Low site quality (high ground).
Eleocharis acuta R.Br. (Cyperaceae)	Rarely flooded areas; low site quality areas subjected to water logging from winter rains.
Gnaphalium involucratum Forst (Compositae)	Generally on high ground. Found to colonize high site quality areas during repeated non-flood year.
Inula graveolens (L) Desf. (Compositae)	Species colonizing areas subjected to regular flooding.

Lactuca serriola (L.) (Compositae)	Unflooded or rarely flooded areas.
Ludwigia peploides (Kunth.) P.H.Raven (Onagraceae)	Species colonizing cultivated areas subjected to regular flooding.
Myriophyllum propinquum A.Cunn. (Haloragaceae)	Primarily a large growing chiefly-submerged fresh water aquatic. Persists in a very reduced state on damp soil. Colonizer of bare soil areas use; site quality 1-3.
Oxalis corniculata L. (Oxalidaceae)	Rarely flooded areas; low site quality.
Polygonum aviculare L. (Polygonaceae)	Colonizer of bare soil areas; high site quality in the absence of flooding.
Polygonum hydropiper L. (Polygonaceae)	Species colonizing bare soil areas subjected to regular flooding.
Polygonum minus Huds. (Polygonaceae)	Species colonizing bare soil areas subjected to regular flooding.
Polygonum plebeium R.Br. (Polygonaceae)	Colonizing bare soil areas on high site quality in the absence of flooding.
Solanum esuriale Lindl. (Solanaceae)	Unflooded or rarely flooded areas.
Wahlenbergia fluminalis (J.M.Black) Wimmer ex H. Erchler (Campanulaceae)	Colonizer of bare soil areas, site quality 3.

APPENDIX 2

River Murray Flows Gauged at Tocumwal, May-December Inclusive, 1886-June 1977

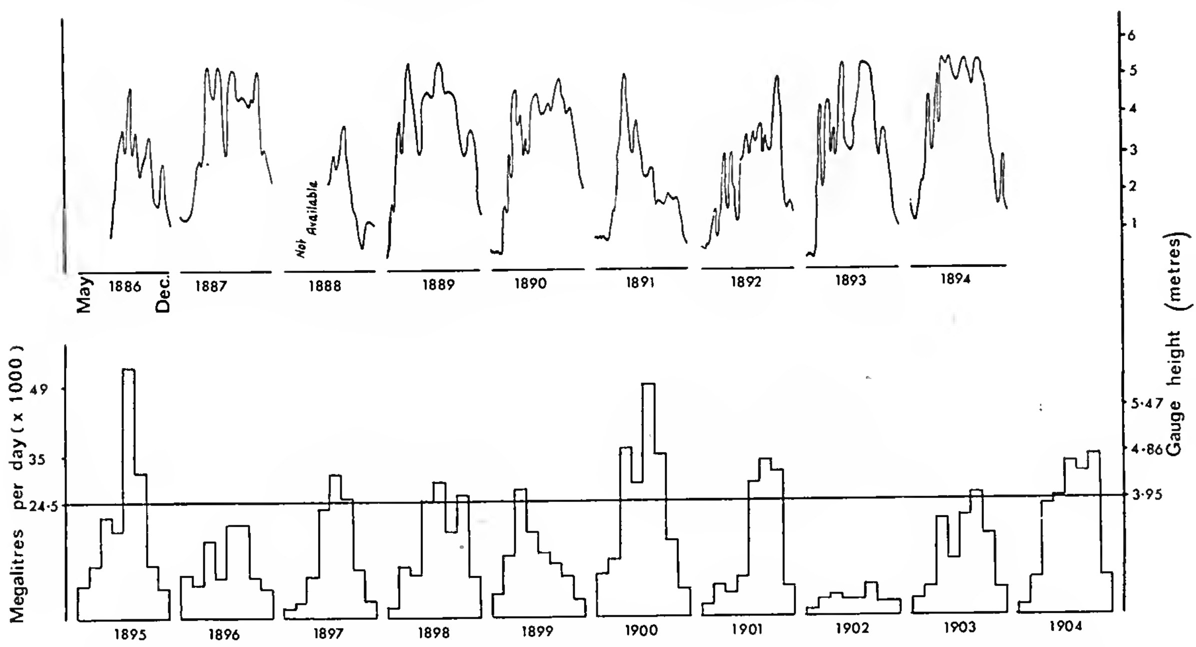

FIG. A2,1 — Flow profile from August 1886 to December 1894, followed by average monthly discharges in Ml per day for the months May to December inclusive. (Covers years 1886-1904.)

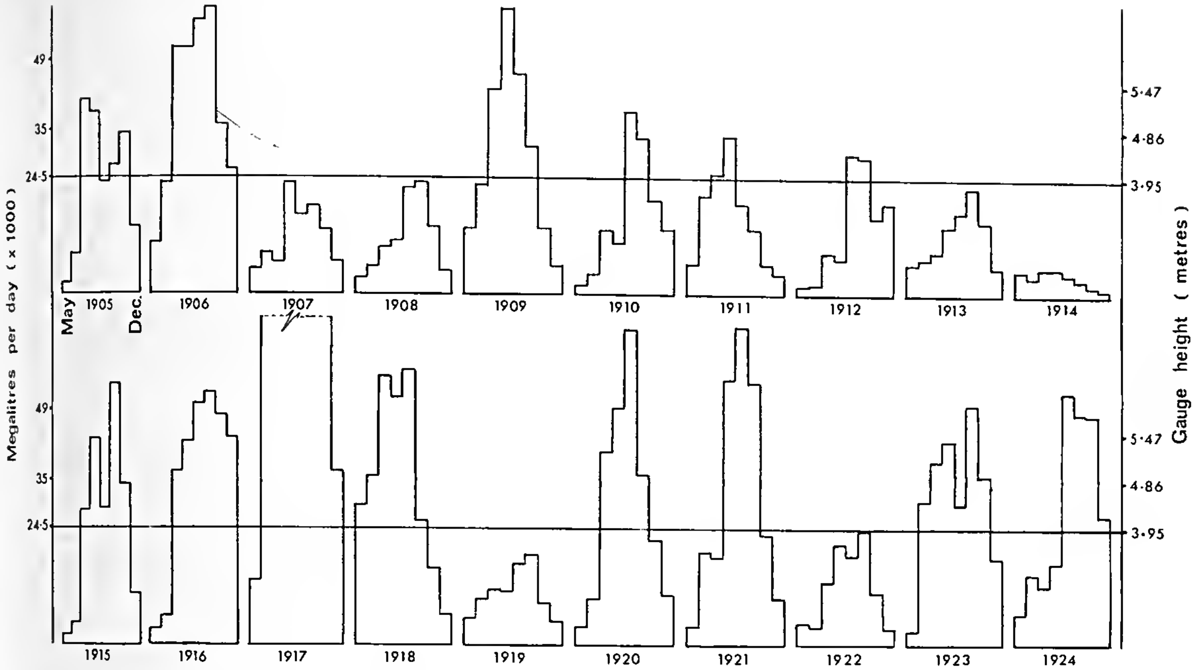

FIG. A2,2 — Average monthly discharges in Ml per day for the months May to December inclusive.

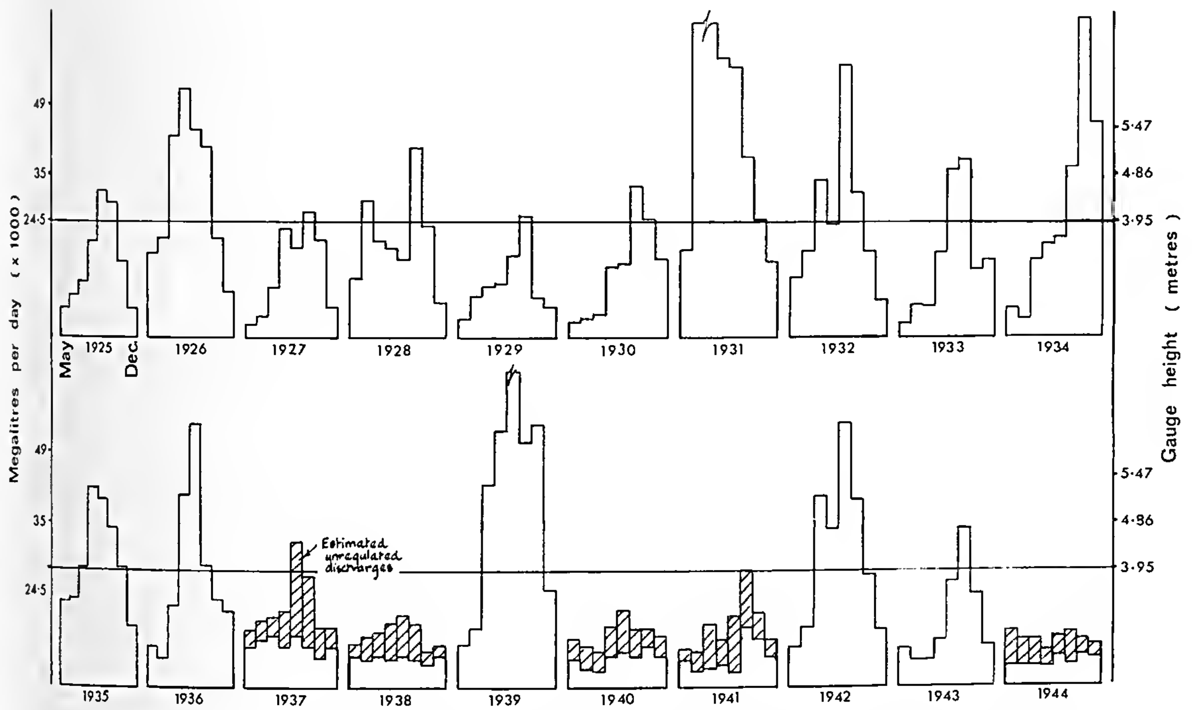

FIG. A2,3 — Average monthly discharges in Ml per day for the months May to December inclusive. From 1934 (Hume Reservoir completed) regulated discharges are shown, but in dry years estimated natural discharges are also shown. (Covers years 1925-1944.)

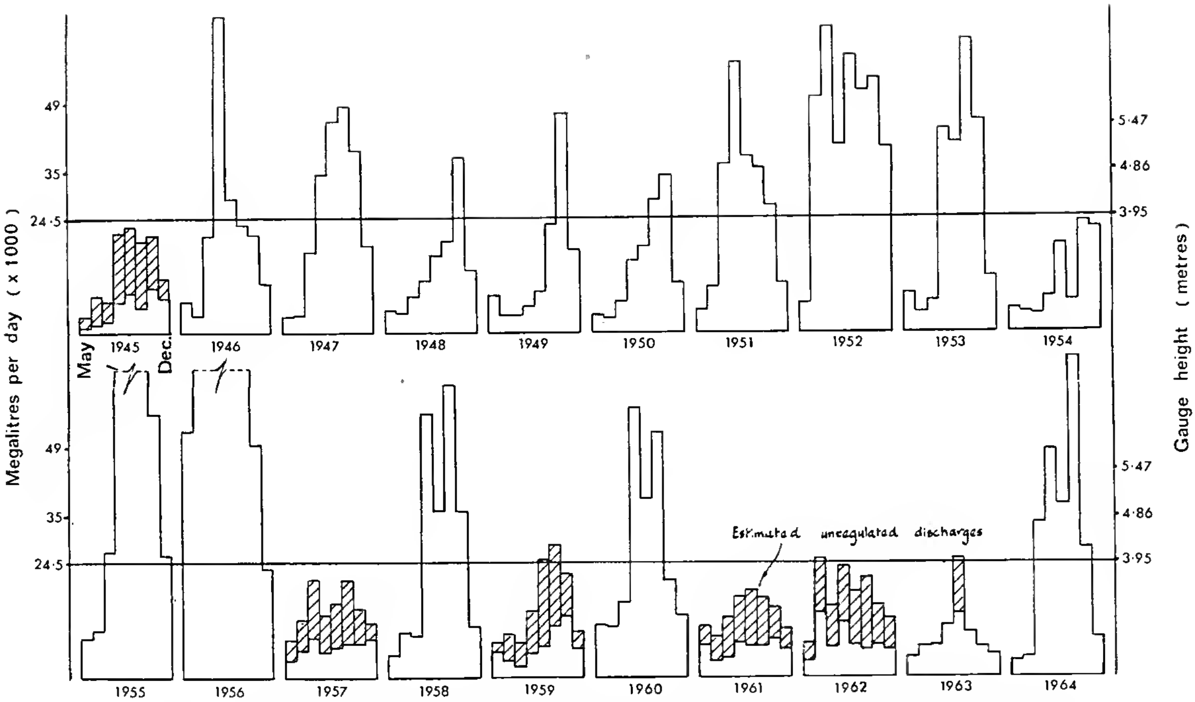

FIG. A2,4 — Regulated monthly discharges in Ml per day for the months May to December inclusive. In dry years estimated natural discharges are also shown. (Covers years 1945-1964.)

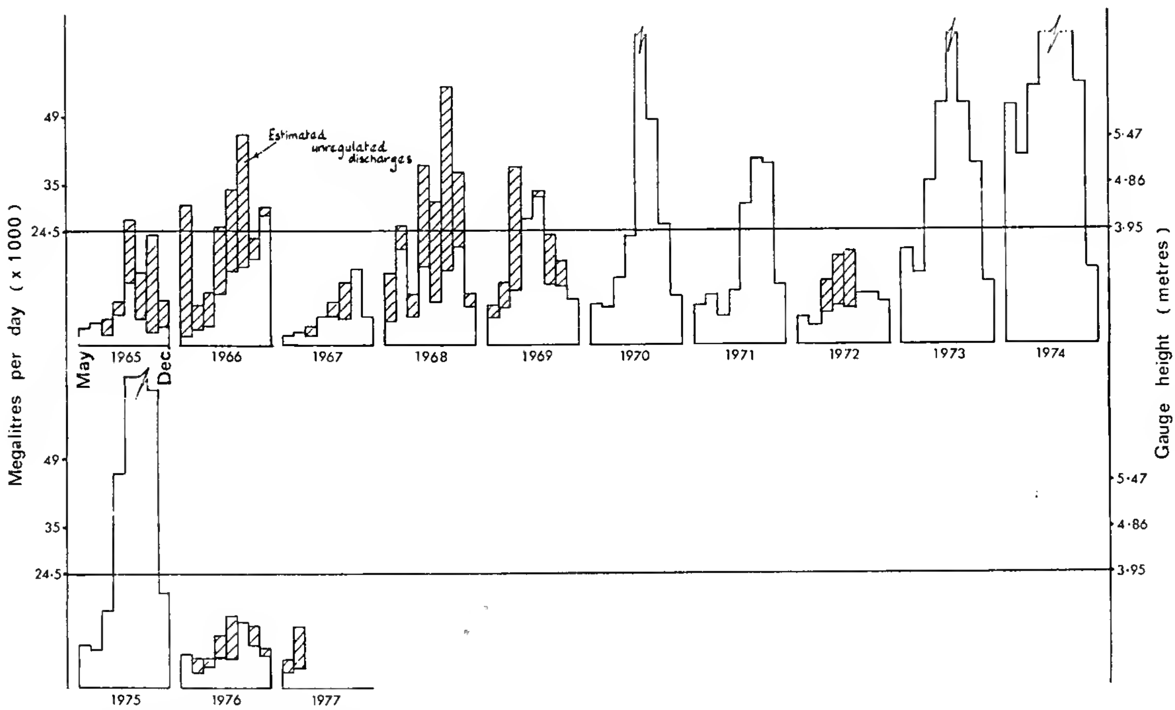

FIG. A2,5 — Regulated monthly discharges in Ml per day for the months May to December inclusive. In dry years estimated natural discharges are also shown. (Covers years 1965-1977.)

APPENDIX 3

Effect of Storage Capacity in Lake Victoria and of Forest Regulators on Flooding of Barmah Forest

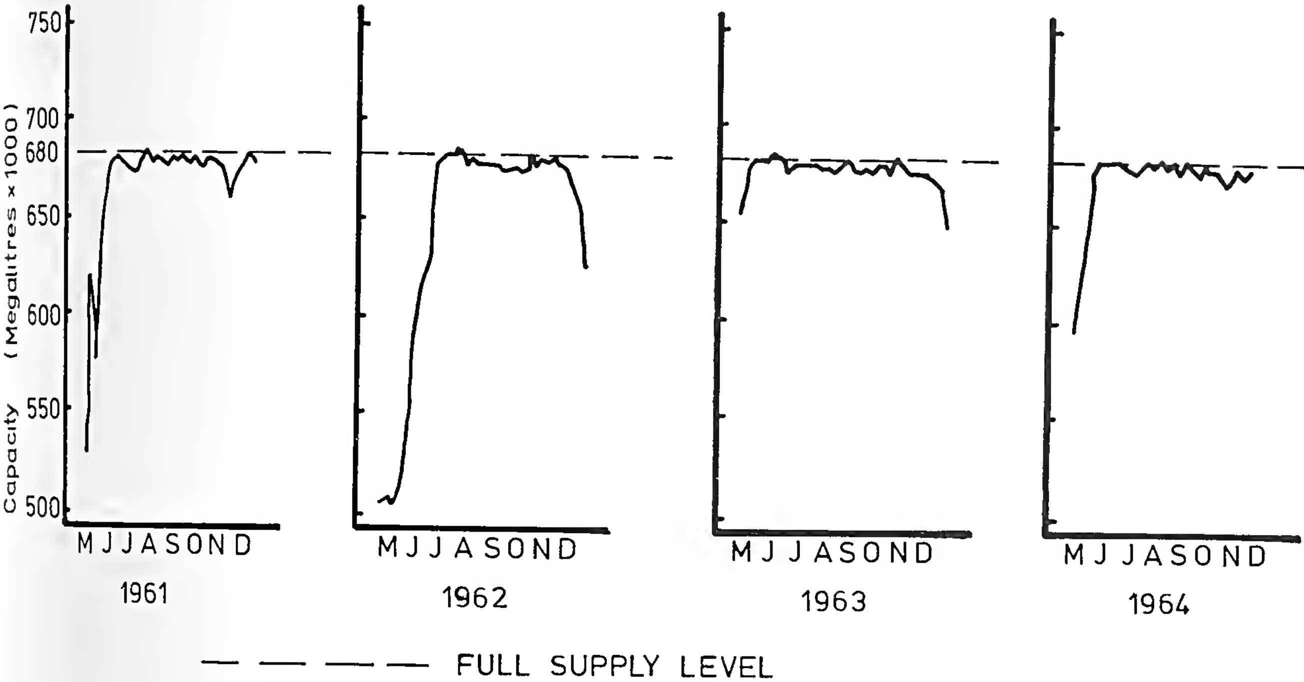

FIG. A3,1 — Storage capacity at Lake Victoria in relation to full supply level for May to December inclusive, 1961 to 1964.

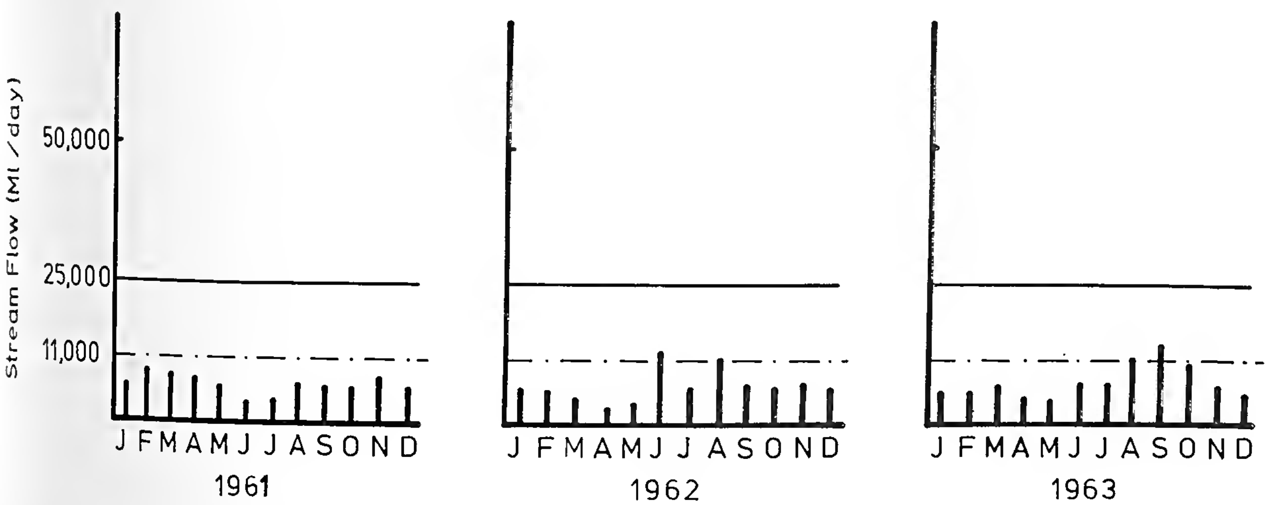

FIG. A3,2 — Stream flow profiles for the Murray River at Tocumwal. Average monthly discharges in Ml/day. January to December inclusive, 1961 to 1963.

ZOOPLANKTON COMMUNITIES OF THE MURRAY-DARLING SYSTEM

A Preliminary Report

By R. J. SHIEL*

ABSTRACT: Data are presented from a continuing study of Murray-Darling planktonic and littoral microfauna, with comparisons from similar studies of large river systems elsewhere. One hundred and twenty-six identified taxa, predominantly Rotifera, Cladocera, Ostracoda and Copepoda are listed, with distributional data. Twelve per cent of these are new genera or species, or new records from Australia. The zooplankton fauna of the river system is seen as a lacustrine assemblage derived principally from upstream impoundments, and inoculated from backwaters and billabongs in time of flood. Slow flow, moderate temperatures (11–28°C) and the still waters of locks and weirs contribute to the persistence of this limnoplankton assemblage in the lower Murray, despite high turbidity.

INTRODUCTION

The importance of the Murray-Darling System as a source of water for multiple use, particularly irrigation and domestic supply, is well-reported, as is the increasingly deleterious effect of such use on water quality. Increasing salinity levels, exacerbated by irrigation practices, and the costly treatment of algal blooms to permit water abstraction for domestic supply are two major problems of the lower Murray.

In view of the importance of the river system to four States, and the vast area of the basin (over a million km^2), it is remarkable that so little information is available on the ecology of the rivers and their impoundments, or on the effects of multiple use on this complex lotic ecosystem.

Extensive reviews of riverine studies elsewhere are provided by Hynes (1970) and Whitton (1975). These sources note the use of aquatic invertebrates, including plankton assemblages, as indicators of water quality. Such data are lacking for the Murray-Darling. Indeed, Bayly and Williams (1973, p. 135) note that 'from the amount of work that has been published on the ecology of Australian rivers and streams, limnologists outside Australia could well be forgiven for thinking that no running water exists here at all'.

The only intensive study to include aspects of invertebrate ecology of the Murray is that of Gutteridge, Haskins and Davey (1974) for the Cities Commission. This study, undertaken in the Albury-Wodonga area, is confined to the area likely to be most affected by urban development of the twin cities: Lake Hume and its environs, and the Murray and its floodplain for a distance of 200 km to Lake Mulwala. The study is further considered by Walker and Hillman (1978).

The present sampling programme was commenced in 1976 to provide baseline ecological information on the invertebrates of the Murray-Darling, with particular emphasis on the potamoplankton. Its aims are: to provide a systematic account of the planktonic fauna of the major impoundments, rivers and tributaries of the system; to assess the characteristic plankton assemblages as indicators of water quality; to provide an account of the complex ecology of billabongs and their relation to the river; and to determine if the autochthonous plankton shows adaptations to the special conditions of the lower Murray, which has high turbidities (Secchi transparency $<$ 10 cm), low and variable flow, and relatively high salinities (up to 1,000 ppm).

MATERIALS AND METHODS

Qualitative samples were taken with standard plankton and Birge cone nets in both horizontal and vertical hauls. Quantitative samples were collected in a modified 30-l perspex trap (Schindler 1969).

*Department of Zoology, University of Adelaide, G.P.O. Box 498, Adelaide, South Australia 5001.

Identifications were made of dissected specimens mounted in PVA lacto-phenol, using keys by Bayly (1961, 1962, 1963, 1964), Goulden (1968), Morton (in prep.), Smirnov (1971), and Smirnov and Timms (in prep.).

SAMPLING STATIONS

Fig. 1 and Table 1 show location of sampling stations. Sampling frequency varied from bi-weekly in the lower Murray to monthly or each season in more distant areas of the basin. Stations were selected to enable longitudinal comparisons of faunal composition to be made, and to cover as thoroughly as possible the watershed of each impoundment, major tributaries and downstream river tracts.

RESULTS AND DISCUSSION

Representative data from selected stations only are presented here. A further twelve-month sampling programme is planned. Trends are already clear from data collected, and a reasonably complete checklist of both planktonic and littoral micro-invertebrates can be given (Table 2). In addition to the tabled species, Protozoa (particularly *Difflugia*, *Arcella* and the dinoflagellate *Ceratium*), and a diverse macro-invertebrate assemblage were frequently collected in the

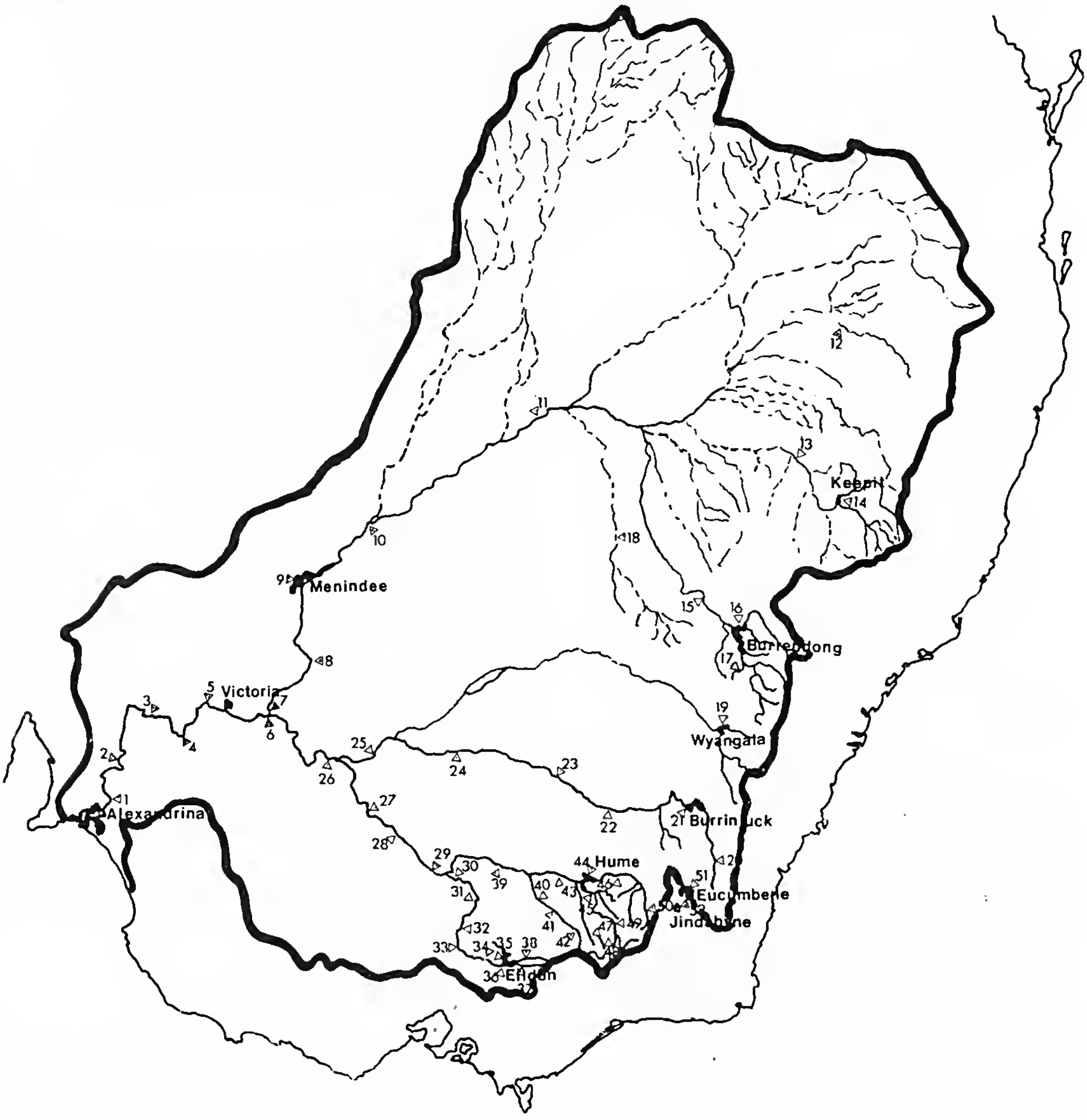

FIG. 1 — Sampling stations on the rivers and impoundments of the Murray-Darling System. Localities are given in Table 1.

TABLE 1
THE LOCATION OF SAMPLING STATIONS SHOWN IN FIG. 1.

Station Number	Locality	Station Number	Locality
1	Murray R., Tailem Bend	27	Murray R., Swan Hill
2	Murray R., Mannum	28	Murray R., Cohuna
3	Murray R., Waikerie	29	Murray R., Echuca
4	Salt Ck., Loxton	30	Goulburn R., McCoy's Bridge
5	Murray R., Renmark	31	Lake Victoria, Shepparton
6	Murray R., Mildura	32	Goulburn Res., Nagambie
7	Darling R., Wentworth	33	Goulburn floodplain, Seymour
8	Darling R., Pooncarrie	34	Goulburn floodplain, Alexandra
9	Lake Menindee	35	Lake Eildon
10	Darling R., Wilcannia	36	Lake Eildon pondage, Eildon
11	Darling R., Bourke	37	Goulburn R., Jamieson
12	Macintyre R., Goondiwindi	38	Howqua R., Howqua
13	Namoi R., Narrabri	39	Lake Mulwala, Yarrawonga
14	Keepit Res.	40	Ovens R., Wangaratta
15	Macquarie R., Dubbo	41	Ovens R., Bright
16	Burrendong Res.	42	Ovens R., Harrietville
17	Macquarie R., Bathurst	43	Murray floodplain, Wodonga
18	Bogan R., Nyngan	44	Lake Hume
19	Wyangala Res.	45	Kiewa R., Tallangatta
20	Eumarella Ck., Bredbo	46	Murray R., Corryong
21	Burrinjuck Res.	47	Rocky Valley Dam, Falls Ck.
22	Murrumbidgee R., Wagga Wagga	48	Mitta Mitta R., Mitta Mitta
23	Murrumbidgee R., Narrandera	49	Mitta Mitta floodplain, Bullhead Ck.
24	Murrumbidgee R., Hay	50	Murray R., Tom Groggin
25	Murrumbidgee R., Balranald	51	Lake Eucumbene
26	Murray R., Euston	52	Lake Jindabyne

plankton. Table 3 lists macro-invertebrates commonly recorded. Most groups are recorded as components of the riverine plankton elsewhere (Hynes 1970). A detailed analysis of this drift component of the Murray zooplankton will be considered at a later date.

In Table 2, for ease of discussion, the sampling area has been divided into three major river systems, two billabong areas, and impoundments.

A greater diversity of species occurs in the billabongs, which have sheltered, still waters, abundant hydrophytes, high nutrient levels and much habitat partitioning. Eighty-three taxa of Rotifera and microcrustacea have been recorded from a single billabong near Alexandra, to date the most diverse microfaunal assemblage recorded from any freshwater habitat. It is likely that a similar complex community exists in billabongs of the Murray. The disparity between the two billabong areas studied reflects the greater intensity of sampling on the Goulburn during an earlier study (Shiel 1976).

Two major groups of microfauna are largely confined to billabongs and marginal weedbeds elsewhere — chydorid Cladocera and Ostracoda. The chydorids *Chydorus sphaericus* and *Alona rectangula*, and the ostracod *Cypretta* are frequently recorded in limno- and potamoplankton. These three taxa are regarded as facultatively limnetic (*sensu* Hutchinson 1967) and are considered with the limnoplankton. Several other chydorid species are infrequently recorded in the plankton in times of flood. These are regarded as littoral 'strays' washed out of hydrophyte beds.

Other genera predominantly recorded from billabongs, but occasionally in the plankton, are *Simocephalus*, *Ilyocryptus* and *Echinisca*. Salient points about the remaining genera are considered *seriatim* below.

Rotifera: More than 50% of the species collected remain unidentified, a reflection of the paucity of taxonomic work on the Australian Rotifera. However, many genera are predictably cosmopolitan (cf. Hutchinson 1967, Ruttner-Kolisko

TABLE 2

Species recorded in the plankton and littoral microfauna of A: *Murray river.* B: *Billabongs of the Murray floodplain between Albury-Wodonga and Yarrawonga.* C: *Goulburn River.* D: *Billabongs on the Goulburn floodplain between Eildon and Seymour.* E: *Darling River.* F: *Major impoundments.*

		A	B	C	D	E	F
Rotifera							
1.	*Brachionus quadridentatus*	●	●				●
2.	*B. novae zealandia*	●	●			●	
3.	*B. calyciflоris*	●					●
4.	*Hexarthra intermedia*						●
5.	*Keratella quadrata australis*	●		●	●	●	●
6.	*K. valga*	●	●	●	●	●	●
7.	*K. cochlearis*	●				●	●
8.	*K. tropica*	●	●	●			
9.	*Keratella* sp. nov.	●	●			●	
10.	*Notholca* sp.	●	●		●		
11.	*Euchlanis incisa*	●					
12.	*Lepadella* sp.	●					
13.	*Lecane luna*	●		●	●		●
14.	*Asplanchna brightwelli*	●	●	●	●	●	●
15.	*Polyarthra vulgaris*			●		●	●
16.	*Filinia longiseta*	●	●			●	
17.	*F. pejleri*	●	●			●	●
18.	*Conochilus dossuarius*	●				●	●
Cladocera							
19.	*Diaphanosoma excisum*			●		●	●
20.	*D. unguiculatum*			●	●	●	●
21.	*Latonopsis australis*		●				
22.	*Pleuroxus aduncus*	●				●	
23.	*Pleuroxus* sp.	●					
24.	*Alonella excisa*		●		●		
25.	*Chydorus sphaericus*	●	●		●		●
26.	*C. eurynotus*		●				
27.	*Dunhevedia crassa*		●		●		
28.	*Pseudochydorus globosus*		●		●		
29.	*Alona rectangula rectangula*	●	●		●		●
30.	*A. rectangula richardi*				●		
31.	*A. davidi davidi*		●				
32.	*A. davidi iheringi*		●		●		
33.	*A. cambouei*	●	●		●		
34.	*A. guttata*	●			●	●	●
35.	*Graptoleberis testudinaria*		●	●	●		
36.	*Kurzia latissima*		●	●	●		
37.	*Camptocercus australis*		●		●		
38.	*Leydigia leydigii*		●		●		
39.	*L. australis*	●					
40.	*Biapertura affinis*		●	●	●	●	

Table 2 (continued)

	A	B	C	D	E	F
41. *B. intermedia*				●		
42. *B. kendallensis*				●		
43. *B. rigidicaudis*	●	●		●		
44. *B. karua*				●		
45. *B. setigera*		●		●		
46. *Monospilus* sp. nov.	●					
47. *Scapholeberis mucronata*		●		●		
48. *S. kingi*				●		
49. *Daphnia carinata*	●				●	●
50. *D. lumholtzi*	●	●			●	●
51. *Simocephalus exspinosus australiensis*		●		●		●
52. *S. vetulus elisabethae*		●		●		
53. *S. vetulus gibbosus*		●				
54. *S. acutirostris acutirostris*		●			●	
55. *Ceriodaphnia dubia*				●		
56. *C. laticaudata*				●		
57. *C. cornuta*	●		●		●	●
58. *C. quadrangula*	●	●	●	●	●	●
59. *Moina tenuicornis*						●
60. *M. micrura*	●	●		●	●	●
61. *Bosmina meridionalis*	●	●		●	●	●
62. *B.* cf. *longirostris*	●				●	
63. *Neothrix armata*				●		
64. *Pseudomoina lemnae*				●		
65. *Echinisca* spp.	●	●				
66. *Ilyocryptus sordidus*	●			●		
67. *I. spinifer*	●	●	●	●	●	●
68. *Macrothrix spinosa*		●		●		●
69. *Macrothrix* sp.	●					
Ostracoda						
70. *Ilyodromus ellipticus*				●		
71. *I. smaragdinus*				●		
72. *Stenocypris* sp.				●		
73. *Candona* sp. "A" sp. nov. (cf. *Cypris stobarti*)		●				
74. *Candona* sp. "B" sp. nov.				●		
75. *Candonocypris candonoides*		●				
76. *Strandesia* sp. nov.				●		
77. *Newnhamia fuscata*		●				
78. *N. fenestrata*		●				
79. *Cyprinotus leana*				●		
80. *Potamocypris* sp. nov.				●		
81. *Herpetocypris* sp.				●		
82. *Diacypris* sp. nov.				●		
83. *Ilyocypris* sp. "A"				●		
84. *Ilyocypris* sp. "B"				●		
85. *Cypretta* sp. "A" sp. nov.				●		
86. *Cypretta* sp. "B" sp. nov.				●		
87. *Cypretta* sp. "C" sp. nov.		●				
88. *Cypretta* sp. "D" sp. nov.		●				

Table 2 (continued)

	A	B	C	D	E	F
89. *Paracypria minuta*				●		
90. unidentified gen. nov. sp. nov.				●		
91. unidentified spp.	●	●	●	●		
Copepoda						
92. *Attheyella incerta*				●		
93. *A. australica*	●	●		●		
94. *Attheyella* sp. nov.		●		●		
95. *D. Arcithompsoniid* gen. nov.				●		
96. *Elaphoidella* sp.				●		
97. *Microcyclops varicans*	●	●		●		●
98. *Microcyclops* sp. 2				●		
99. *Microcyclops* sp. 3			●	●		●
100. *Microcyclops* sp. 4	●				●	
101. *Ectocyclops medius*		●		●		
102. *Eucyclops euacanthus*		●		●		●
103. *E. agilis*	●	●		●		●
104. *Eucyclops* sp.				●		
105. *Paracyclops chiltoni*		●		●		
106. *Macrocyclops albidus*		●	●	●		●
107. *Acanthocyclops vernalis*		●		●		
108. *Mesocyclops leuckarti*	●	●	●	●	●	●
109. *Mesocyclops* cf. *decipiens*						●
110. *Tropocyclops* cf. *confinus*	●	●	●	●		
111. *Tropocyclops* sp.				●		
112. *Tropocyclops* sp. nov.				●		
113. *Gladioferens spinosus*						●
114. *Calamoecia lucasi*				●	●	●
115. *C. australica*						●
116. *C. expansa*				●		●
117. *C. ampulla*	●				●	●
118. *Hemiboeckella searli*				●		
119. *Boeckella minuta*		●		●		
120. *B. major*						●
121. *B. fluvialis*		●	●	●	●	●
122. *B. delicata*						●
123. *B. triarticulata*	●	●	●	●	●	●
Amphipoda						
124. *Austrochiltonia australis*		●		●		
Isopoda						
125. *Heterias* sp.				●		
Decapoda						
126. *Paratya australiensis*	●	●		●		
127. *Macrobrachium* sp.	●	●				

TABLE 3
MACRO-INVERTEBRATES COMMONLY COLLECTED IN THE MURRAY-DARLING PLANKTON

Taxon	Predominant groups(s)
Coelenterata	Hydrozoa – *Chlorohydra, Hydra, Craspedacusta sowerbyi*
Platyhelminthes	Turbellaria
Aschelminthes	Gastrotricha, Nematoda
Mollusca	Bivalvia – glochidia of the Murray River mussel, *Velesunio ambiguus* and/or *Alathyria jacksoni*
Annelida	Naididae – *Chaetogaster* sp.
Arthropoda	Tardigrada
	Insecta – Collembola
	Ephemeroptera, Odonata, Plecoptera – nymphal stages
	Hemiptera – Belostomatidae, Notonectidae, Corixidae
	Coleoptera – Dytiscidae, Gyrinidae, Hydrophilidae
	Trichoptera – Hydroptilidae (nymphs)
	Diptera – Chironomidae
	Arachnida – Hydracarina, Porohalacaridae

1974). Ten of the eighteen species are listed by Whitton (1975) as common river zooplankton. Notably, eight of the Murray rotifer species (species code 1, 4, 5, 6, 7, 14, 15, 16 in Table 2) are recorded by Whitton as indicators of eutrophic conditions in rivers. Several of these species are common in Lake Hume, where conditions verging on eutrophy have been documented (Gutteridge, Haskins & Davey 1974).

Cladocera: Of the 51 species recorded, eleven are regarded as true plankters (19, 20, 49, 50, 57, 58, 60, 61, 62) or facultatively planktonic (25, 29). The seasonal occurrence of *Macrothrix* (69) in the lower Murray is noted. This is normally a littoral genus (Hutchinson 1967). Its presence in the plankton may be a response to algal blooms, high turbidity and the low flow after the dry summer of 1976-77 which brought about 'pond' conditions. All other planktonic species were recorded from upstream impoundments and river tracts, and seven of the eleven occur in Lake Alexandrina at the Murray mouth (M. C. Geddes, pers. comm.). All genera recorded are common to both lakes (Hutchinson 1967) and rivers (Whitton 1975).

Copepoda: The Harpacticoida recorded are littoral forms rarely occurring in the plankton. The cosmopolitan cyclopoid genera *Mesocyclops, Eucyclops* and *Microcyclops* are all represented in the potamoplankton. Of the calanoid copepods listed, only two species occurred throughout the basin (*C. ampulla* and *B. triarticulata*). However, some species were recorded over wide areas (*C. lucasi, B. fluvialis*); others had limited distributions (*C. expansa, C. australica, B. delicata, B. major*).

Distributional differences in plankton assemblages are indicated by Fig. 2, which shows autumn limnoplankton composition in ten selected impoundments. In seven of these, the limnoplankton was dominated by Copepoda, predominantly *C. ampulla, B. triarticulata* and cyclopoid copepodites. Copepoda were also present in the other three impoundments, but the cladoceran *Bosmina* dominated in Eildon (35); a dinoflagellate, *Ceratium*, predominated in Burrendong (16; also present in large numbers in Hume, 44); and seven species of rotifers comprised 60% of the plankton in Menindee (9; especially *Filinia longiseta* and *Keratella quadrata australis*).

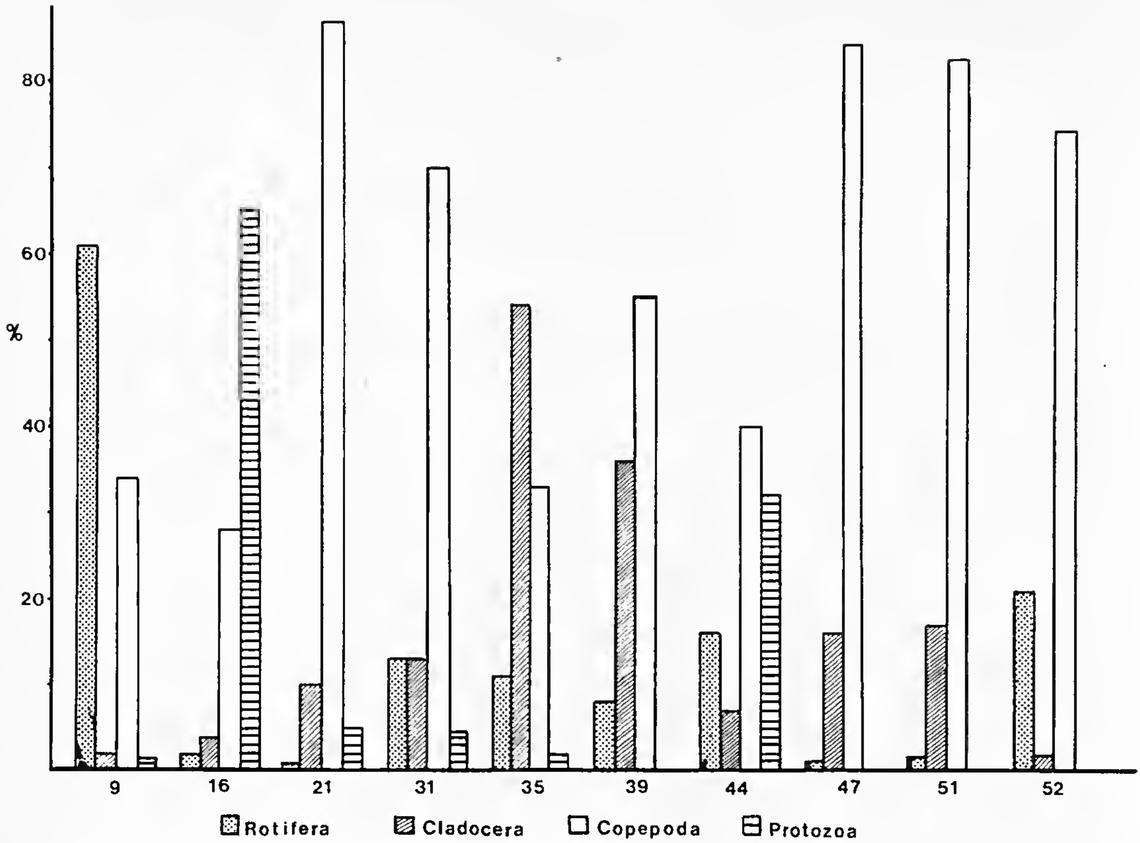

FIG. 2 — Comparative limnoplankton composition (%) of ten selected impoundments in autumn, 1977. See Table 1 for localities.

Plankton densities varied from < 20 — 30 l^{-1} in the nutritionally dilute alpine lakes to > 200 l^{-1} in Hume and Burrendong.

In the case of Lake Menindee, its extreme shallowness (< 3 m), turbidity (< 10 cm transparency), and its 'riverine' features may have contributed to the differences in plankton. Differences in nutrient levels may account for the compositional changes in Hume and Burrendong, but comparative data are lacking.

The occurrence of lacustrine assemblages below the dams varies seasonally and with individual impoundments, depending on the output from the dam. In Lake Eildon, for example, the outlet to the power station is at 52 m in the hypolimnion (I. J. Powling, pers. comm.). When the lake stratifies in summer, plankters are absent from the deoxygenated hypolimnion, and consequently are absent from the outfall below the dam. After overturn in May/June, plankters may survive passage through the turbines. In the winter of 1974, when Eildon overflowed, and the spillway gates were opened, a lacustrine plankton was collected in the pondage below the dam, and lake species were recorded from the flooded billabongs at Alexandra, 20 km downstream (Shiel 1976). The 1974-75 flooding did not, however, significantly flush the Alexandra billabong fauna into the Goulburn. The moderating effect of Eildon reservoir, gentle downstream gradients and relatively wide floodplain allowed a slow rise in water level which led to lateral movement of the zooplankton populations into fringing *Juncus* beds, with protection from the minimal current flow (Shiel 1974).

This flood-mitigating feature of impoundments has undoubtedly promoted the maintenance of a lacustrine plankton. Below Hume, Lake Mulwala provides relatively still waters, extensive backwaters, and littoral weedbeds. Below Eildon, complex plankton communities are found in the Goulburn Weir at Nagambie, and Lake Victoria at Shepparton.

Significantly, the Darling, the least impounded of the major rivers in the system, has a plankton composition numerically dominated by Rotifera, and most closely approximating the rotifer-dominated riverine assemblages noted by Hynes (1970) and Whitton (1975).

The contribution in flow of the Darling to the lower Murray varies markedly. The greatest proportion of flow to the lower Murray is from the Murray-Goulburn catchment, with seasonal peaks from the Darling. Two such flood peaks occurred in summer, 1976, and autumn, 1977.

Below the confluence of the two rivers at Wentworth there are no significant tributaries. Zooplankton assemblages recorded in the lower Murray reflect, therefore, the contributions from each system and the seasonal fluctuations therein. The mixing of the two inputs produces a zooplankton assemblage which persists for about 500 km to Lake Alexandrina. Low gradients (1 — 2 cm per km) and significant nutrient inputs from downstream towns and irrigation areas contribute to produce a slow-moving series of more or less discrete 'slugs' of water in which algal blooms are frequent. Nuisance blooms of *Anabaena, Melosira, Microcystis* and *Oscillatoria* are most common. The zooplankton composition of each 'slug' varies with source, temperature and perhaps food availability.

Fig. 3 shows the fluctuation in zooplankton composition recorded at Mannum over a period of 16 months. Cladocera and Copepoda, predominantly *Bosmina meridionalis, Ceriodaphnia quadrangula* and *Boeckella triarticulata*, dominate the plankton, with seasonal occurrences of *Moina micrura* and *Ceriodaphnia cornuta*. Two peaks of Rotifera (*Brachionus quadridentatus* and *Keratella valga*) were noted in summer and autumn, coinciding with floodwaters from the Darling. Only two rotifer species were frequently collected over the study period — *Asplanchna brightwelli* and *Keratella quadrata australis*.

Domination of the zooplankton by Cladocera and Copepoda suggests that the Murray has characteristics of both lotic and lentic systems, characteristics which may change seasonally. Hynes (1970) noted that crustaceans, important in still waters, are rarely important in rivers, where rotifers dominate. He also noted (1969) the poor development of the plankton generally, as compared with still waters. Neither statement strictly applies to the Murray.

In studies on the Nile, Monakov (1969) and Rzoska (1976) noted that increasing impoundment of the river favours the development and maintenance of lake plankters in the river. Many of the cosmopolitan rotifer and microcrustacean species collected in the Murray system are recorded from Nile impoundments; however, cataracts and rapids on the latter system have a devastating effect in selectively removing plankters. Similarly, the seasonal flooding of the Nile system largely obliterates the plankton (Rzoska 1976). These effects are not seen in the Murray-Darling, with gentler physiography and lower rainfall. Seasonal dilution of the Murray plankton occurs in times of

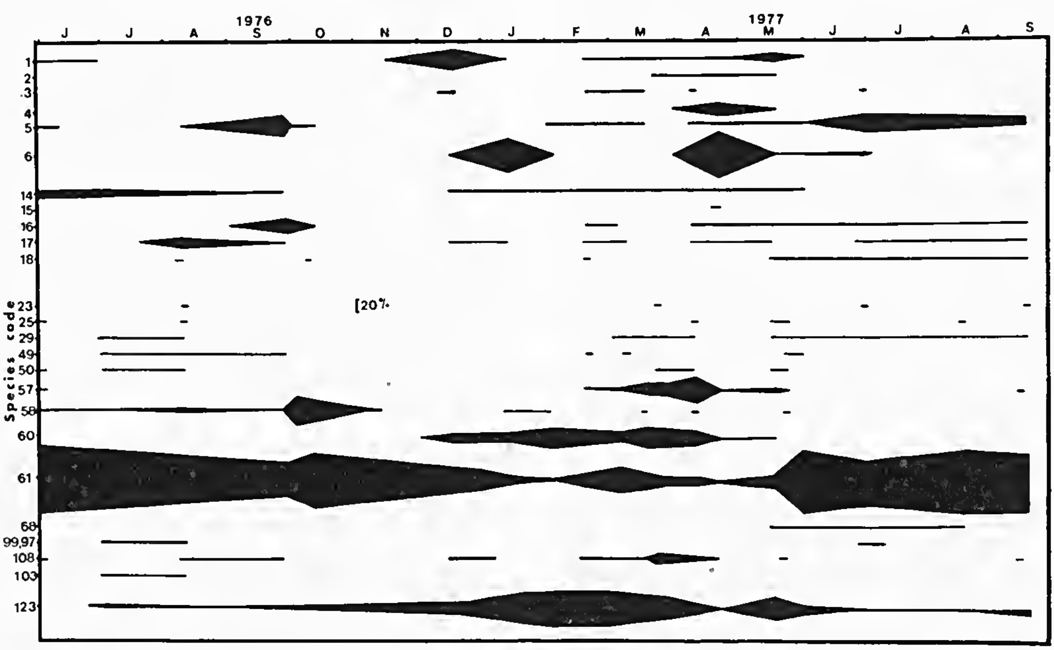

FIG. 3 — Seasonal compositional changes in riverine plankton at Mannum, S.A. See Table 2 for species code.

flood, but there is little elimination of plankters. Diversity actually increases as plankton of backwaters and non-planktonic inhabitants of billabongs are washed into the river.

In summary, the composition of the zooplankton of the lower Murray is closer to that of upstream impoundments than to a true riverine plankton. Indeed, it more closely resembles the community of permanent ponds. The plankton of such ponds in Australia generally includes *Boeckella triarticulata, Mesocyclops leuckarti, Daphnia lumholtzi, D. carinata, Ceriodaphnia cornuta, Alona rectangula, Chydorus sphaericus* and *Asplanchna.* All of these species are recorded from a variety of ponds (as well as lakes, impoundments and billabongs) in eastern Australia (Jolly 1968, Timms 1970a, b, 1973, Bayly & Williams 1973, Shiel 1976). Their widespread distribution in such diverse habitats suggests adaptation to a range of physico-chemical and biological parameters, the extremes of which are not exceeded in the Murray-Darling System.

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19

MOLLUSCS OF THE MURRAY-DARLING RIVER SYSTEM

By BRIAN J. SMITH*

ABSTRACT: The Murray-Darling River System, draining over a million km² from south Queensland to Victoria, is one of the major river systems of the world. However its low annual flow, the arid nature of much of its surrounding land and regular drought cycles combine to give the area a surprisingly depauperate fauna. The aquatic mollusc fauna of the rivers and flood plains consists of 24 species, which can be divided into those directly associated with the rivers and those found only in standing or low flow waters away from rivers. Almost all the species directly associated with the rivers show close affinities with widespread northern Australian species, whereas the remainder are mainly allied with the southeastern and east-central faunas. The terrestrial mollusc fauna of the flood plains consists of about 50 species, over a third of which are species introduced into Australia. In certain groups of this fauna there is also evidence of affinities with northern forms.

The Murray-Darling Basin has been looked on as a faunal region, particularly for aquatic fauna. It is suggested here that this river system should rather be regarded as a transportation corridor. Many of the fluviatile species and some of the terrestrial species show close affinities to, and are the southernmost members of, diverse groups found in northern Australia, and it is suggested that these southern extensions are caused by flood transport. Over a third of the terrestrial molluscs are species introduced into Australia and their distribution pattern strongly suggests introduction by human river traffic.

INTRODUCTION

The Murray-Darling River System, draining over a million km² of southern and central Australia from Queensland to Victoria is one of the major river systems of the world. However for a major drainage system it has a remarkably low annual flow. This is because of its comparatively small mountain catchment area, and the dry, arid nature of much of the country through which it flows. These conditions are further aggravated by regular severe drought cycles which can impose periods of extreme environmental stress on the biota. These factors combined result in a surprisingly depauperate fauna, when the size and habitat diversity of the system is taken into consideration.

The Murray-Darling is really two separate systems which join fairly close to their distal ends. One is fed from snow-melt and confined to the southeastern region of Australia. The other, fed from tropical monsoon water, runs from and through two biotic regions different from the southeastern region where the two systems join. This difference in water source and hence times of peak flow in the two sub-systems can cause backflows which provide a possible explanation for biotic interchange. McMichael and Iredale (1959) considered the Murray-Darling as a single faunal province for aquatic molluscs, the Mitchellian Fluvifaunula, citing three characteristic species, *Velesunio ambiguus*, *Alathyria jacksoni* and *Plotiopsis balonnensis*.

There have been no comprehensive studies of the molluscan fauna of the Murray-Darling System or even of the two separate sub-systems. Collections of molluscs have been acquired from many localities, particularly along the Murray, in conjunction with the distribution survey of non-marine molluscs of southeastern Australia (Smith & Plant 1973). However the only published work on the fauna has been either taxonomic treatise such as McMichael and Hiscock (1958), Gabriel (1939) or Iredale (1937b, 1943) which give some information on this fauna, or results of survey work for small regions within the system such as for the Mitta Mitta Valley (Smith, Malcolm & Morison 1977).

MAIN HABITAT TYPES

A number of main habitat types can be identified

*Senior Curator (Zoology), National Museum of Victoria, Russell Street, Melbourne, Victoria 3000.

each containing a different molluscan faunal assemblage. The aquatic habitats are characterized by water source and quality, flow regime, sediment and nutrient load, bottom type and the presence or absence of aquatic vegetation. Terrestrial habitats are characterized by available moisture, type of vegetation and soil and rock type.

The principal aquatic habitats are the rivers and major tributaries themselves and their associated flood-filled lagoon and billabong systems. In the upper reaches of the source rivers where the bed slope is still great and the rate of flow fast, the streams are characterized by alternating riffle-rapid and pool systems, the dissolved oxygen is high and the suspended solid load usually low (Smith *et al.* 1977). Aquatic vegetation is usually present only in backwaters and the main benthic habitats are either between the stones in the boulder stretches or in the fine sediments of the pools. As the bed slopes decrease the rate of flow and stream carrying capacity drops and the rivers occupy deep meandering channels in alluvial silt. The bottom composition is mainly a fine silt and the suspended solid content of the stream is greatly increased, reducing light penetration. Because the width and depth of the rivers has increased, and they are also subject to periodic massive floods, large dead trees are carried by the streams. These become lodged as submerged snags, creating a hard surface substrate in localities otherwise devoid of such sites. The water quality in these sections of the rivers is lowered through an increase in dissolved salts due to soil leaching and the effects of irrigation.

Other permanent water habitats closely associated with the rivers on the flat land are the lagoons and billabongs formed from isolated old meanders of the rivers. These are replenished by overtopping in flood times, but for the rest are cut off from the main stream and become stagnant. They are enriched by stock excreta, run-off carrying pasture fertilizer, and by terrestrial and aquatic vegetation rotting down and forming highly productive eutrophic systems with massive production of algae and other aquatic vegetation and aquatic animals.

Similar in many ways to the lagoon systems are the marshes and dams also found on the flood-plains. These, too, are eutrophic systems showing high productivity. However they are not formed and fed by the rivers but are above and separate from the river systems. This means that no direct water transport of aquatic animals is possible between the river and the marshes and dams. There are also occasional saline lakes found away from the rivers in this area.

Another significant aquatic habitat is found in the flood zones of the rivers. An example is the Barmah Forest. In times of flood such areas are inundated and remain under water for many months, providing very large areas of high productivity aquatic habitat with a fine silt substratum and abundant hard surfaces. However, these areas are subject to periodic dry periods which prevent the establishment of aquatic flora and fauna that is incapable of withstanding such dry conditions.

A major aquatic habitat superimposed on the natural system in the last hundred years is found in the extensive irrigation systems of both the Murray and Darling Basins. These systems have large transport canals carrying river water to land above and beyond the normal flood influence of the rivers. The canals and channels provide large bodies of water in which aquatic fauna can develop, and these form large new aquatic habitats, altering the balance of the entire system.

The terrestrial habitats to be considered in this study are confined to the enlarged flood plains of the rivers. In the upper reaches these consist of areas of dry sclerophyll forest and marginal bush with large trees and deep litter. Forest areas, particularly of *E. camaldulensis*, also occur in the central and lower reaches, where fallen logs and deep leaf-litter provide favourable habitats for land molluscs. In the northern part of the area the flood plains are dry, arid areas with saltbush, spinifex and other semi-desert vegetation. In the southern region, after the two rivers have combined, the Murray River is bordered by high limestone cliffs which provide a totally different terrestrial habitat.

However the dominant factor influencing the character of much of the terrestrial habitat bordering the rivers is the modification of the environment by European man. Large areas of the river flats have been cleared for monoculture of introduced plants such as wheat, vines, citrus trees and conifers, and major centres of human habitation with exotic garden plants have been established. Irrigation raises the available moisture level in these habitats to an average throughout the year far above the normal level for the area. These centres are also localities where road, rail and river transport discharges cargo originating in far distant places, and hence a source of accidental introduction of exotic animals.

AQUATIC FAUNA

Twenty-four species of aquatic molluscs (see Appendix) have been recorded from the combined river systems and many are widespread throughout.

TABLE 1
DISTRIBUTION OF AQUATIC MOLLUSCS OF THE MURRAY-DARLING SYSTEM

SPECIES	STREAMS & IRRIGATION CHANNELS	LAGOONS	MARSHES	SALT LAKES
Vivipara (N.) hanleyi	+			
Potomopygus nigra	+			
Pupiphryx grampianensis	+			
Coxiella striata				+
Gabbia australis	+	+		
Plotiopsis balonnensis	+	+		
Lymnaea lessoni		+	+	
Lymnaea tomentosa		+	+	
Planorbarius corneus	+			
Physastra gibbosa		+	+	
Glyptophysa cosmeta		+		
Glyptophysa aliciae	+	+		
Bulinus (I.) hainesii	+	+	+	
Bulinus (I.) newcombi		+	+	
Gyraulus sp.	+			
Segnitila sp.		+	+	
Ferrissia (P.) petterdi	+	+	+	
Ferrissia (P.) tasmanica	+	+	+	
Velesunio ambiguus	+	+		
Alathyria jacksoni	+			
Alathyria condola	+			
Corbiculina angasi	+			
Pisidium casertanum	+	+	+	
Sphaerium sp.		+	+	

The fauna is most easily considered as four assemblages: (1) the rivers and streams; (2) the lagoons and associated systems; (3) the freshwater habitats separated from the rivers and (4) the salt lakes. The distribution of the species between these assemblages is set out in Table 1. The assemblage listed under the heading of streams and irrigation channels encompasses virtually all the flowing water in the system. However the species listed in this assemblage are not equally distributed throughout the system.

The two species of hydrobiids, *Potomopyrgus nigra* and *Pupiphryx grampianensis*, and the planorbiid, *Gyraulus* sp., are confined to the upland streams of northeastern Victoria. The two planorbiids *Bulinus* (*Isidorella*) *hainesii* and *Glyptophysa aliciae* are found in shallow back-waters and other localities with a good growth of aquatic vegetation in the southern section of the system. Similarly the two species of freshwater limpets, *Ferrissia* (*Pettancylus*) *petterdi* and *F.* (*P.*) *tasmanica*, and the pea shell *Pisidium casertanum* are also found in the shallow, high quality waters of the inflow streams in the southern section of the system. However this latter observation is probably a false picture due to a paucity of detailed collecting in the northern streams.

Most of the species listed for this assemblage have been collected from various parts of the irrigation systems connected with the rivers in Victoria, South Australia and New South Wales. The little basket shell, *Corbiculina angasi* has been reported (G. A. Buchanan, pers. comm.) as a fouling organism of reticulation pipes and sprinkler systems in the Mildura area, while large populations of *Plotiopsis balonnensis* have been collected from concrete channels around Mildura. The freshwater mussels are found in the large main water transport channels of the system. One interesting record is the introduced planorbiid, *Planorbarius corneus*, which has been recorded from one or two channels in the Sunraysia district of Victoria and New South Wales (Smith 1969).

The main interest in this assemblage is however the group of species thought of as typical of the Murray-Darling System (McMichael & Iredale 1959). These are *Vivipara* (*Notopala*) *hanleyi*, *Gabbia australis*, *Plotiopsis balonnensis*, *Velesunio ambiguus*, *Alathyria jacksoni* and *Alathyria condola*. These species are all members of families

and genera with a widespread distribution in northern and central Australia and, with the exception of *Velesunio ambiguus*, are the southernmost members of these groups. *Velesunio* also occurs in the coastal streams of Victoria and Tasmania and a fossil species of *Alathyria* has been recorded from the Eocene beds of the Launceston Basin in Tasmania (McMichael & Hisock 1958), though the genus is not represented there at the present time. However the distribution of all these forms is consistent with the idea that they are southern extensions of diverse northern Australian groups, transported south and east along the Murray-Darling System probably in times of flood.

The lagoon and marsh assemblages are very similar in character with many species in common. These common species reflect the habitat types of these communities: both are eutrophic with a heavy growth of aquatic vegetation. Such forms as the two *Lymnaea* spp., *Physastra gibbosa*, the two *Bulinus* spp., *Segnitila* sp., the two freshwater limpets and the two pea shell species fall into this category. However in addition the lagoon systems have several species, directly derived from the rivers, which are not present in the marsh systems. These are many of the species listed above as being typical of the river system. One species, *Glyptophysa cosmeta* has only recently been recorded from the Murray Basin (Smith & Burn 1976) and its capacity to aestivate as a method of overcoming the intermittent dry periods to which the flood zones are subject has been described.

There are several isolated salt lakes in the area and these support a single species of mollusc, *Coxiella striata*, especially adapted to that environment.

TERRESTRIAL FAUNA

The Murray-Darling System flows through three faunal regions of eastern and central Australia. These are the southeastern region, the east coast region and the central region. The terrestrial fauna of the various parts of the system is characteristic of those areas, with no evidence of any unified Murray-Darling fauna. However, as with the aquatic fauna, the present distribution of several terrestrial species can most easily be explained if one invokes transportation down the river corridors in times of flood.

The fauna of the upper reaches of the Victorian feeder streams is typical of the dry sclerophyll forest areas north of the Divide. It consists of one or two charopid species, the camaenid *Chloritobadistes victoriae* and the rhytidid *Rhytida* (?) *capillacea*, together with one or two introduced species. Down on the lower flood plains of the Murray Valley the fauna consists largely of several punctid species in the leaf litter, particularly around the base of *E. camaldulensis*. A great many introduced species of snails and slugs are seen in the man modified habitats and several, such as *Cernuella* (*Cernuella*) *virgata* and *Theba pisana*, are major pests of vine, orchard and grain crops in the irrigated areas. Sixteen species of introduced snails and slugs are recorded for the region. Most are pests and occur in large numbers in the irrigated and urban areas.

The terrestrial mollusc fauna of the upper reaches of the feeder streams west of the Divide in the Darling system of northern New South Wales and southern Queensland is very poorly known. The rhytidid *Strangesta* (?) *strangei* and the camaenid *Galadistes bourkensis* occur together with one or two charopids. The flood plains of the Darling system are dry and arid with saltbush and sparse vegetation. The mollusc fauna of this area is typical of the central Australian fauna with the camaenid genera *Sinumelon* and *Pleuroxia* predominating together with *Glyptorhagada* and *Meracomelon* in northeastern South Australia. Several pupillids are also common in this dry northern part of the system. Many of these forms are typical of central Australia and find their southern range limits in the lower reaches of the Murray-Darling System.

Three groups of land snails are of particular interest from the point of view of indicating possible effects on faunal distribution of the Murray-Darling System. These are the camaenids, the rhytidids and the pupillids. All these groups are in need of comprehensive taxonomic revision, but even without an up-to-date evaluation of the groups certain suggestions can be put forward about interrelationships.

In the family Camaenidae there is a wide radiation of subglobose species with slight granular sculpture and closed umbilicus typified by species belonging to the genera *Meriodolum* and *Galadistes* in the upper reaches of the Darling system. In shell structure and in some general anatomical feature they show similarities with the group of species belonging to the genera *Meracomelon* and *Sinumelon* found in central South Australia around the past and present lower reaches of the river.

The family Rhytididae has a group of medium to large species, referred to the genus *Strangesta*, inhabiting Queensland and northern New South Wales including the upper reaches of the Namoi and adjacent rivers. A species, *Strangesta* (?)

gawleri, found in the Lofty Ranges and around the lower Murray shows several similar features to the *Strangesta* group (Smith, unpublished). There are no similar species in southern New South Wales or Victoria.

The family Pupillidae is a widespread, common group in central Australia with two genera, *Gastrocopta* and *Pupoides* particularly prominent. Both these groups have their southern limit in the wide flood plains and limestone cliffs of the southern end of the Murray-Darling System.

DISCUSSION

The Murray-Darling River System is really two separate river complexes draining two totally different types of land areas in eastern Australia. These two rivers join close to their seaward end and flow as a combined stream for only a comparatively short distance relative to their total lengths. However, from the point of view of their associated fauna, the fact that they are separate systems that eventually come together has important implications. The rivers, fed by entirely separate and unrelated water sources, are both subject to periodic massive floods. Because one may be in flood while the other is at a low flow stage of its cycle there is the potential for considerable fauna dispersal between the two systems.

The area has often been considered as a single faunal province. Iredale (1937a) incorporated most of the Murray-Darling Basin in his Euronotian Faunula of land shells and McMichael and Iredale (1959) designated the aquatic molluscs of the Basin the Mitchellian Fluvifaunula. Five species of aquatic molluscs are here considered endemic to the Murray-Darling System but there are no endemic terrestrial mollusc species. The species considered endemic to the Murray-Darling System are:

Vivipara (*Notopala*) *hanleyi*
Plotiopsis balonnensis
Glyptophysa cosmeta
Alathyria jacksoni
Alathyria condola

The molluscan faunas of the various parts of the system are more closely related to the molluscan assemblages in areas adjacent to those parts. The molluscan assemblage of the Murray Basin is typically southeastern Australian in composition, that of the upper reaches of the feeder streams of the Darling system is typical of the eastern Australian fauna and that of the lower Darling typical of central Australia.

While the molluscs of the Murray-Darling System do not appear to form a faunal unit, several species do represent the southern-most range distributions of widespread, diverse northern Australian groups. Groups such as the Viviparidae and Thiaridae are found in the river systems of much of Queensland, Northern Territory and northwestern Australia. However in the southern regions they are confined to the Murray-Darling System, with their southern limit the freshwater boundary of the lower Murray. Certain genera of land molluscs show a similar picture with widespread northern groups and related groups occurring in the lower Murray Valley but with no close relatives in the remainder of the southeastern Australian faunal region. Though much more detailed taxonomic revisionary work needs to be undertaken to confirm the relationships, these observations suggest that the Murray-Darling System has had a significant influence on the distribution of animals in eastern Australia. It is suggested that the Murray-Darling System should be considered a transportation corridor, bringing about, by means of the periodic massive floods to which the system is subject, the distribution of several molluscan species from northern and to a lesser extent southeastern Australia in the Lower Murray Valley.

Over the past hundred and fifty years, European settlement has brought about major habitat changes in the Murray-Darling System with river flow control, land clearance and the establishment of large areas of urbanization and monoculture of introduced plant species. To service this development river, rail and road transport systems have been established. These activities have caused the widespread dispersal of introduced snails and slugs to the point where these species are now the dominant molluscs, particularly in the Murray Valley where many have reached plague proportions.

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APPENDIX

Species list of the molluscs recorded from the Murray-Darling River System. I = *species introduced into Australia;* E = *species endemic to this river system.*

AQUATIC FAUNA

Family Viviparidae
(E) *Vivipara* (*Notopala*) *hanleyi* (Frauenfeld, 1862)
Family Hydrobiidae
Potomopyrgus nigra (Quoy and Gaimard, 1835)
Pupiphryx grampianensis (Gabriel, 1939)
Coxiella striata (Reeve, 1842)
Family Bithyniidae
Gabbia australis (Tryon, 1865)
Family Thiaridae
(E) *Plotiopsis balonnensis* (Conrad, 1850)
Family Lymnaeidae
Lymnaea lessoni (Deshayes, 1831)
Lymnaea tomentosa (Pfeiffer, 1855)
Family Planorbidae
(I) *Planorbarius corneus* (Linne, 1758)
Physastra gibbosa (Gould, 1847)
(E) *Glyptophysa cosmeta* (Iredale, 1943)
Glyptophysa aliciae (Reeve, 1862)
Bulinus (*Isidorella*) *hainesii* (Tryon, 1866)
Bulinus (*Isidorella*) *newcombi* (Adams & Angas, 1864)
Gyraulus sp.
Segnitila sp.
Family Ancylidae
Ferrissia (*Pettancylus*) *petterdi* (Johnston, 1879)
Ferrissia (*Pettancylus*) *tasmanicus* (Tenison-Woods, 1876)
Family Hyriidae
Velesunio ambiguus (Philippi, 1847)
(E) *Alathyria jacksoni* (Iredale, 1934)
(E) *Alathyria condola* (Iredale, 1943)
Family Corbiculidae
Corbiculina angasi (Prime, 1864)
Family Sphaeriidae
Pisidium casertanum (Poli, 1795)
Sphaerium sp.

Terrestrial Fauna

Family Succineidae
Succinea (*Austrosuccinea*) *australis* (Ferussac, 1821)
Family Pupillidae
Gastrocopta (*Australbinula*) *rossiteri* (Brazier, 1875)
Gastrocopta (*Australbinula*) *bannertonensis* (Gabriel, 1930)
Gastrocopta (*Austrálbinula*) *margaretae* (Cox, 1868)
Pupoides adelaidae (Angas, 1864)
Pupoides beltiana (Tate, 1894)
Pupoides ischna (Tate, 1894)
Family Valloniidae
(I) *Vallonia pulchella* (Muller, 1774)
Family Rhytididae
Rhytida (?) *capillacea* (Ferussac, 1832)
Strangesta (?) *gawleri* (Brazier, 1872)
Strangesti (?) *strangei* (Pfeiffer, 1849)
Family Charopidae
Elsothera murrayana (Pfeiffer, 1864)
Stenopylis hemiclausa (Tate, 1894)
Pillomena dandenongensis (Petterd, 1879)
Gyrocochlea sp.
Family Punctidae
Paralaoma morti (Cox, 1864)
Laomavix collisi (Brazier, 1877)
Magilaoma penolensis (Cox, 1868)
Excellaoma retipora (Cox, 1867)
Paralaoma sp.
Family Arionidae
(I) *Arion intermedius* (Normand, 1852)
Family Zonitidae
(I) *Oxychilus alliarius* (Miller, 1882)
(I) *Oxychilus cellarius* (Muller, 1774)
Family Milacidae
(I) *Milax gagates* (Draparnaud, 1801)
Family Limacidae
(I) *Limax maximus* (Linnaeus, 1758)
(I) *Deroceras caruanae* (Pollonera, 1891)
(I) *Deroceras reticulatus* (Muller, 1774)
(I) *Lehmannia* (*Lehmannia*) *nyctelia* (Bourguignot, 1861)
(I) *Lehmannia* (*Limacus*) *flavus* (Linnaeus, 1758)
Family Camaenidae
Chloritobadistes victoriae (Cox, 1868)
Meracomelon cassandra (Pfeiffer, 1864)
Sinumelon fodinalis (Bednall, 1892)
Sinumelon flindersi (Angas, 1864)
Exilibadistes sutilosa (Deshayes, 1850)
Semotrachia subsecta (Tate, 1879)
Meridolum gilberti (Pfeiffer, 1846)
Pleuroxia hinsbyi (Gude, 1916)

Galadistes bourkensis (Smith, 1891)
Glyptorhagada silveri (Angas, 1868)
Glyptorhagada kooringensis (Angas, 1877)

Family HELICIDAE

(I) *Helix (Cryptomphalus) aspersa* (Born, 1778)
(I) *Theba pisana* (Muller, 1774)
(I) *Cernuella (Cernuella) virgata* (Da Costa, 1779)
(I) *Candidula intersecta* (Poiret, 1801)
(I) *Cochlicella ventrosa* (Draparnaud, 1801)
(I) *Cochlicella acuta* (Muller, 1774)

20

SOME CAUSES OF THE DECLINE IN RANGE AND ABUNDANCE OF NATIVE FISH IN THE MURRAY-DARLING RIVER SYSTEM

By P. L. CADWALLADER*

ABSTRACT: Various authors have reported a decline in the range and abundance of many native fish in the Murray-Darling System. Several factors may have contributed to this decline. Hydro-electric, irrigation and water conservation schemes have altered the flow and thermal regimes of many rivers, thereby adversely affecting the reproductive ability of those native fish which require specific minimum water temperatures and floods as triggering mechanisms for spawning and subsequent survival of eggs and young. Dams act also as physical barriers to the movements of fish. Forestry and farming practices and land clearing in the upper reaches of the system have caused changes in the pattern of run-off, leading to increased siltation. This has probably reduced the reproductive success of fish which lay adhesive eggs on the substrate, and has caused also the filling in of previously deep holes, thereby removing part of the habitat of fish such as cod. Desnagging and channelization of rivers have removed native fish cover and spawning sites. Fish kills have been caused by heavy metal pollution and by the agricultural application of compounds such as Lindane, Aqualin and Endrin, and many fish have been found to contain sub-lethal amounts of insecticide residues. Introduced trout have fragmented the ranges of some galaxiids and have probably had adverse effects on trout cod, Macquarie perch and blackfish. Other introduced fish have probably adversely affected the native fish fauna, but information on the effects of introduced fish on native fish is usually anecdotal and fragmentary. Considerable further work is required on the factors affecting the range and abundance of native fish, and the results of this work should be used for determining future river management policies.

INTRODUCTION

Excluding essentially marine species which are sometimes found in the lower reaches of the Murray, there are 26 species of native fish in the Murray-Darling River System (Table 1). These fish have evolved in an unpredictable and widely-fluctuating environment in which large natural fluctuations in population size are to be expected (Mackay 1973). However, Macquarie perch and trout cod are now rare and seriously threatened with extinction, and the distribution and/or abundance of catfish, golden perch, Murray cod and blackfish have been reduced as a result of man's activities (Williams 1967, J. S. Lake 1976b, 1971, Berra 1974). The distribution and abundance of many of the smaller species, such as galaxiids, have also been affected (Pollard & Scott 1966, J. Frankenberg 1971), but little is known about the biology or the past distribution of many of these species.

There are many ways in which man's activities have affected the distribution and abundance of native fish. Some have resulted in direct fish kills, but, in most instances, the effects have been indirect or of a sub-lethal and chronic nature. Because our knowledge of this fauna is so poor we can, in many instances, only speculate on the effects that man's past activities may have had on the native fish.

HYDRO-ELECTRIC, IRRIGATION AND WATER CONSERVATION SCHEMES

At present, about 10% of the world's total stream flow is regulated by man (Croome *et al.* 1976). In the Murray-Darling Basin, extensive hydro-electric, irrigation and water conservation schemes have resulted in the regulation of the flow of many rivers, and nearly half the mean natural flow of the system is now drawn off for irrigation and urban use (Frith 1973). The Murray itself is regulated by weirs and dams at intervals from the Hume Dam

*Snobs Creek Freshwater Fisheries Research Station and Hatchery, Private Bag 20, Alexandra, Victoria, 3714.

TABLE 1
NATIVE FISH OF THE MURRAY-DARLING RIVER SYSTEM

Modified from J.S. Lake (1975). The taxonomy of some of the groups, e.g. the Galaxiidae, is presently under review.

Family	*Species*	*Common name*
Petromyzontidae	*Mordacia mordax* (Richardson)	Short-headed lamprey
Clupeidae	*Fluvialosa richardsoni* (Castelnau)	Bony bream
Retropinnidae	*Retropinna semoni* (Weber)	Australian smelt
Galaxiidae	*Galaxias maculatus* (Jenyns)	Common galaxias
	Galaxias planiceps Macleay	Flat-headed galaxias
	Galaxias findlayi Macleay	Kosciusko galaxias
	Galaxias olidus Günther	Common inland galaxias
	Galaxias oconnori Ogilby	Queensland mountain galaxias
	Galaxias rostratus Klunzinger	Beaked galaxias
Plotosidae	*Tandanus tandanus* Mitchell	Freshwater catfish
Melanotaeniidae	*Nematocentrus fluviatilis* (Castelnau)	Rainbow fish
Atherinidae	*Craterocephalus fluviatilis* McCulloch	Hardyhead
Centropomidae	*Ambassis castelnaui* (McLeay)	Western chanda perch
Percichthyidae	*Macquaria australasica* Cuvier and Valenciennes	Macquarie perch
	Plectroplites ambiguus (Richardson)	Golden perch
	Maccullochella peeli (Mitchell)	Murray cod
	Maccullochella macquariensis (Cuvier and Valenciennes)	Trout cod
Teraponidae	*Madigania unicolor* (Günther)	Spangled perch
	Bidyanus bidyanus (Mitchell)	Silver perch
Kuhliidae	*Nannoperca australis* Günther	Southern pigmy perch
Gadopsidae	*Gadopsis marmoratus* Richardson	River blackfish
Eleotridae	*Philypnodon grandiceps* (Krefft)	Big-headed gudgeon
	Mogurnda mogurnda (Richardson)	Purple-spotted gudgeon
	Hypseleotris klunzingeri Ogilby	Western carp gudgeon
Mugilidae	*Mugil cephalus* Linnaeus	Mullet
Bovichthyidae	*Pseudophrites urvilli* (Cuvier and Valenciennes)	Congoli

upstream of Albury-Wodonga to the saltwater barrage on Lake Alexandrina at its mouth, a distance of 2,200 km. The principal water storages (Table 2) are in the headwaters of the system. In summer, water is released from the dams at a fairly constant rate for irrigation purposes. Irrigation flows cease in autumn and the dams begin to store the normal flows of winter and spring. Generally, the uncontrolled river was high, cool, turbid and fast flowing in spring and early summer and these conditions changed gradually until, by the end of summer, the waters were low, warm, slow flowing and clear (Butcher 1967). Thus, the effects of dams are to reverse the natural pattern of water flow and to reduce the incidence of floods or, at least, cause the flattening out of successive flood peaks (Williams 1967, Wharton 1969). Since water is lost by evaporation from the storage reservoirs, dams also decrease the total runoff.

Because outflow water is invariably taken from near the bottom of a dam, in summer it is much colder than the inflow water, and it must flow for

TABLE 2
PRINCIPAL STORAGES IN THE MURRAY-DARLING DRAINAGE BASIN

Modified from Australian Water Resources Council (1976)

I = *Irrigation*; H= *Hydro-electric*; W = *Water Supply*; F = *Flood Mitigation*

Storage	*River*	*Gross capacity ($m^3 \times 10^6$)*	*Purpose*
Dartmouth*	Mitta Mitta	3700	I, H
Eildon	Goulburn	3390	I, H
Hume	Murray	3038	I, H
Menindee Lakes	Darling	1794	I, W
Burrendong	Macquarie	1680	I, F
Blowering	Tumut	1628	I, H
Copeton	Gwydir	1364	I
Wyangala	Lachlan	1220	I
Burrinjuck	Murrumbidgee	1026	I

* *under construction*

many kilometres downstream before reaching the temperature of the inflow water. For example, at Eildon Reservoir the outflow water comes from 52 m below full supply level, and summer temperatures in the Goulburn River many kilometres below the dam are 10-15°C lower than those of the inflow water (Williams 1967).

These changes in both flow and thermal regimes have had a marked effect on native fish, many of which require specific minimum water temperatures and floods as triggering mechanisms for spawning and the subsequent survival of eggs and young. J. S. Lake (1967a) found that golden perch and silver perch spawn at water temperatures above 23°C provided there is an accompanying rise in water level; Murray cod were found to spawn at 20°C, western carp gudgeon at 22.5°C and catfish at 24°C. Llewellyn (1973, 1974) found that spangled perch spawn at water temperatures of 20° (bottom) to 26°C (surface), and southern pigmy perch at 19.3°-21°C. Flooding helps to induce spawning of spangled perch but is not essential. In the Eildon Reservoir and its inflowing rivers, Macquarie perch were found to require a water temperature of 16.5°C before spawning movements and spawning occurred (Wharton 1968, Cadwallader & Rogan 1977). The colder water and/or the timing and extent of flooding has adversely affected the ability of these species to reproduce. According to J. S. Lake (1975) the Murray from Albury to Euston and beyond now rarely reaches a temperature high enough to induce golden perch to spawn.

Flooding provides ideal conditions for the pelagic eggs of golden perch and silver perch. Such eggs, which are more common in marine fish, are not suited to fast water currents but thrive in relatively tranquil flood-spread waters.

The gradual elimination of the great anabranch or backwater systems of the Murray and its tributaries by water control schemes (including the construction of levee banks which effectively reduce the floodplain area) has reduced the extent of waters which previously provided the necessary space and food for the young of many fish species. In the Murray-Darling River System good year classes of fish such as Murray cod have been produced only following extensive floods at spawning time (J. S. Lake 1971).

Dams and weirs act as physical barriers to the movements of fish. Data on the movements of native fish, particularly golden perch, in the Murray-Darling System have been derived from long-term tagging programmes undertaken by the State fisheries agencies of New South Wales, Victoria and South Australia. Llewellyn (1968) reported that golden perch moved upstream as much as 1,000 km in 163 days, and that upstream movement was closely related to river height (Fig. 1). Movement of fish may also be influenced by temperature, since fish moved less when floods occurred in winter. Reynolds (1976) also reported extensive movements by tagged golden perch (Fig. 2); most of these long-distance upstream movements were recorded from fish released towards the end of September 1975, just before the 1975-76 flood broke over the river banks. It appeared that the massive migration was a result of the flood, but it is not known whether spawning requirements, food requirements or an alteration in water quality triggered the migration. In the past, large numbers of golden perch moving downstream have been taken in drum nets in June and July, when the water has been low (Cadwallader 1977). Although not necessarily directly related to spawning, the upstream movements ensure that spawning occurs upstream of the areas occupied at other times of the year and thereby compensate for any downstream displacement of eggs and recently hatched fish. In the Murray, the abundance of golden perch above Yarrawonga Weir has been greatly reduced and they are very rare as far downstream as Torrumbarry Weir (Lake 1975).

Fishways and fish ladders provide continuity between the fish populations above and below dams, but there are only two such structures in operation on the Murray-Darling River System (Wharton 1969). Their importance to fish

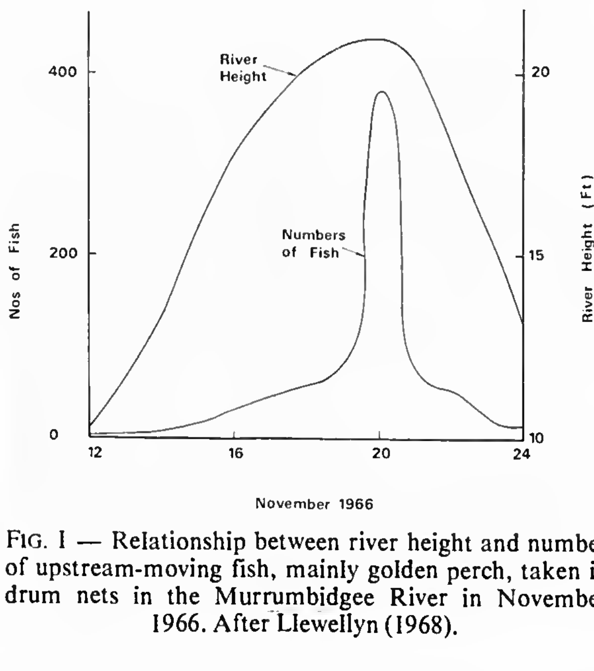

FIG. 1 — Relationship between river height and number of upstream-moving fish, mainly golden perch, taken in drum nets in the Murrumbidgee River in November 1966. After Llewellyn (1968).

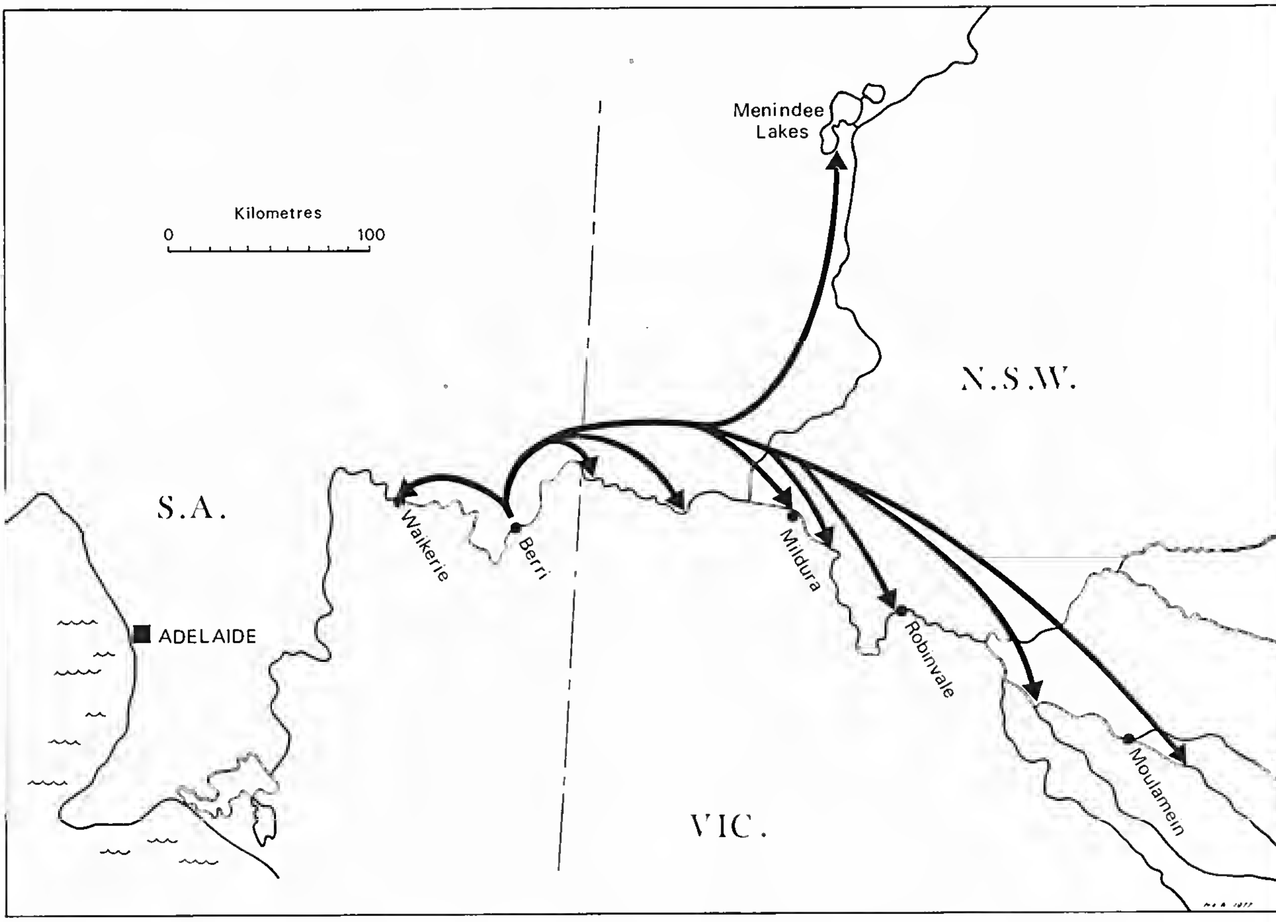

FIG. 2 — Movements of golden perch tagged and released in the Murray River at Berri, South Australia. After Reynolds (1976).

movements is indicated by the numbers of native fish which have been recorded passing through the Euston-Robinvale fish ladder (Fig. 3). The design and efficiency of such structures, particularly for large dams, depends on detailed knowledge of the swimming capabilities and behaviour of the migrating fish. This knowledge is not yet available for Australian native fish. Furthermore, fishways or fish ladders for native fish are of little use unless there are discharges of the appropriate temperature and volume to induce movements. The problem of discharging water of a particular temperature can be overcome to some extent by the use of multi-level offtakes on dams (so that water can be drawn from particular levels), but without the increased flow, the warmer water by itself may be insufficient to stimulate the spawning of fish such as golden perch and silver perch. However, as pointed out by Frith (1973), it should be possible to release water at times appropriate to fish breeding and then retrieve it downstream to be used for other purposes.

Sudden fluctuations in water level caused by irrigation or power generation requirements may have disastrous effects on fish such as western carp gudgeon, which spawn in shallow water over grasses and twigs (Lake 1975). The sudden release of water can displace eggs and young fish to unfavourable situations and a sudden reduction in discharge can leave eggs stranded above water.

As pointed out by Ridley & Steel (1975), a marked reduction in maximum flows and the consequent prevention of flood-time scouring has often led to an increase in the occurrence of macrophytes downstream from large dams. Although the establishment of macrophytes in many backwaters of the Murray-Darling System may not have directly affected the native fish species, the abundant water weeds and reeds in some areas have provided ideal spawning grounds

for introduced fish such as European perch and tench (Cadwallader 1977).

The presence of a dam usually increases the plankton content of the water downstream from the storage, and the benthic fauna is also affected by the changed flow and thermal regimes. Reservoirs also act as settling basins and reducc the turbidity of the water, although some management practices may increase turbidity by the discharge of turbid layers from the reservoir. Water downstream from the dam may also be chemically unusual and contain large quantities of bacteria as well as moribund algae from the hypolimnion (Fraser 1972, Hynes 1972). The effcets of such changes on the fish fauna of the Murray-Darling System have been overshadowed by the effects of changed flow and thermal regimes, and have yet to be evaluatcd.

The large storage reservoirs are usually deep and cold, and generally have lower area-volume ratios than natural lakes of comparable size (Williams 1973). The lack of fringing vegetation in most of the artificial reservoirs is almost certainly due to the fluctuations of the level of the stored water. This lack of vegetation affects the composition and productivity of the associated invertebrate fauna (Williams 1967) and, consequently, the composition and productivity of the fish fauna.

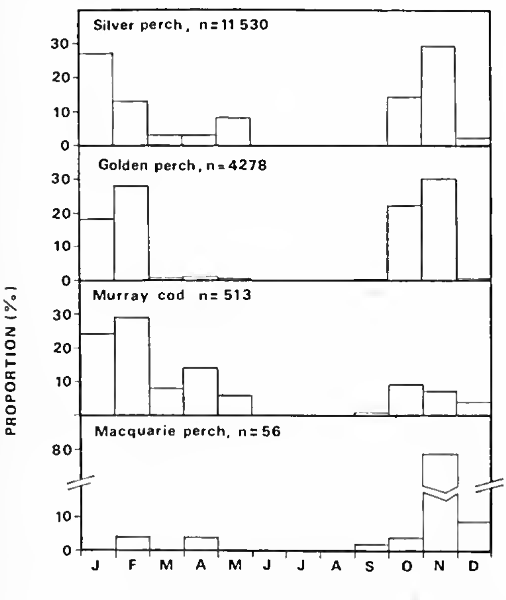

FIG.3 — Monthly variation in the upstream movements of silver perch, golden perch, Murray cod and Macquarie perch as indicated by fish passing through the fish ladder on weir and lock no. 15 (Euston-Robinvale) on the Murray River between 28 May 1938 and 7 November 1942. The histogram for each species represents the proportion of fish passing through the ladder each month as a percentage of the total number of fish of that species passing through the ladder between May 1938 and November 1942. After Cadwallader (1977).

As new storages are filled they flood the surrounding land, and the rotting vegetation liberates abundant nutrients. This leads to an explosive development of fish food. The fish that are able to take advantage of the abundant food available at this time and those that can spawn under the new conditions will flourish. Eventually the productivity of the newly-formed lake will fall and the fishing will inevitably decline (Elder 1965, Lowe-McConnell 1975). At best, in the Murray-Darling Basin, only residual populations of native fish exist in impounded watcrs, which invariably are dominated by introduced species (Butcher 1967). For example, Macquarie perch were once abundant in Eildon Reservoir, but they are now recorded only rarely from the reservoir and its inflowing rivers; the fish fauna of the reservoir now consists predominantly of introduced European perch, goldfish and trout (Cadwallader & Rogan 1977). Following the construction of dams, introduced trout now occur at relatively low altitudes and survive the years of exceptional heat and drought because of the cooler water present in the depths of the large reservoirs (J. S. Lake 1975). Furthermore, trout are able to survive downstream from the reservoirs because of the cold water released from the dams in summer. Impoundments throughout south-eastern Australia have provided additional trout waters and occasionally, e.g. as in the case of Lake Eucumbene (Tilzey 1972), support flourishing fisheries. The effects of trout on the native fish fauna are discussed later.

Another aspect of water management practices that affects native fish is the diversion of rivers from one watershed to another. An example of this is the diversion of the Snowy River from the southeast coastal drainage system to the Murray-Darling River System (Australian Water Resources Council 1976). Such diversions change zoogeographic boundaries and modify natural systems (Butcher 1967). The fisheries implications of water transfers between catchments have recently (1976) been discussed by a joint study group of the Ministry of Agriculture, Fisheries and Food and the National Water Council (U.K.), which concluded that the greatest risk of damage appears to be in producing highly unstable ecological conditions (by transfer of water of different physical and chemical characteristics, transfer of pollutants, transfer of fish and eggs, etc.) and in the widespread dissemination of fish diseases.

LAND CLEARING, FARMING AND FORESTRY PRACTICE

Clearing of land and over-grazing by stock cause changes in the pattern of run-off and lead to increased siltation (Hewlett & Helvey 1970, Bayly & Williams 1973). The removal of trees from large areas of the catchments of many Victorian streams has greatly increased the difference between the maximum winter and minimum summer flows, so that, in extreme cases, originally perennial streams are now intermittent, with obvious consequences for the fish stocks. Burning-off and uncontrolled fires also have important effects. The increase in run-off after a fire has been estimated at about 50%, and the siltation rate is also greatly increased. For example, in the 12 months after the 1939 bushfires the siltation rate in the Eildon Reservoir was greater than that for the preceding 16 years (Williams 1967). Though fires are not a human innovation, there is evidence that they were much less frequent before European man arrived in Australia. Bank erosion caused by poor farming practices (e.g. allowing stock direct access to streams) has led to changes in the general character of many streams, changing them from narrow, clear waters with deep holes to wide, shallow, muddy tracts (Wharton 1969).

Siltation has a number of direct and indirect effects on the native fish fauna, particularly in the upper reaches of the Murray-Darling System. Fish such as Macquarie perch, which lay adhesive eggs on the substrate (Wharton 1968, Cadwallader & Rogan 1977), have probably been the most directly affected by increased siltation. Erosion silt also fills in deep holes, thereby destroying parts of the habitat of Macquarie perch and cod. Apart from blanketing the stream bottom, silt screens out light (thus interfering with the feeding of those fish which feed primarily by sight), changes heat radiation and causes the retention of organic material and other substances which may create unfavourable conditions on the substrate (Ellis 1936). Thus, the composition of the benthic flora and fauna is altered (Cordone & Kelley 1961), with consequent adverse effects on the food chains of the fish.

Recent work in the northern hemisphere has clearly indicated the relation between the nature of the valley through which a stream flows and the productivity of the stream. Upland streams are basically heterotrophic and derive all or most of their energy from organic material elaborated in the watershed (Cummins 1975, Hynes 1975), so that clearing of vegetation in the catchment area changes the productivity of a stream by reducing the input of organic material. As pointed out by P. S. Lake (1976), clear-felling, a major harvesting method of modern intensive forestry carried out in the forested catchments of many streams in southeastern Australia, is probably having extremely damaging effects on the structure and function of stream ecosystems. In addition to reducing the input of organic material, clearing of land right to the edge of streams also increases the amount of sunlight reaching the water, thereby causing an increase in water temperature, which, in turn, influences the levels of oxygen and solids dissolved in the water (Brown & Krygier 1970). Furthermore, the nitrate concentration of a stream flowing from a clear-felled watershed may rise to such an extent that algal blooms, usually rare in streams, may occur in summer (Burton & Likens 1973). Removal of native trees and planting of introduced trees such as pines may also affect the productivity of streams. The fauna of streams has evolved in conjunction with the surrounding terrestrial vegetation, so that the stream invertebrates are able to utilise efficiently the organic material derived from that vegetation. It may be assumed that in headwater streams of the Murray-Darling System the invertebrates are adapted to metabolise organic material from dry and wet sclerophyll eucalypt forests and it is likely that they cannot efficiently utilise organic material derived from a pine plantation (P. S. Lake 1976). In North Carolina, Woodall & Wallace (1972) compared the productivity of four streams, three with non-coniferous vegetation and one with the coniferous white pine (*Pinus strobus*) in their catchments, and found that the stream with the white pine in the catchment supported only one fifth to one half as much animal biomass as the other streams. Differences among the watersheds were attributed to different inputs of allochthonous material. These differences were found even in a part of the world where pines are found naturally and it was concluded that the results 'indicate that forest monoculture practices involving pine watersheds may seriously affect secondary production of aquatic invertebrates' with, no doubt, consequent adverse effects on fish production.

A more direct influence of bank-side vegetation on native stream-dwelling fish was found during a study (Cadwallader & Eden unpublished data) of the summer food of *Galaxias olidus* in streams of the Seven Creeks River System, which drains into the Goulburn River, in Victoria. Arthropods of terrestrial origin form a substantial part of the diet of these galaxiids, which feed in open water and readily take arthropods that fall or alight on the

water surface. An examination of the stomach contents of 30 fish from each of ten sampling stations revealed that the incidence of terrestrial insects in the diet was closely related to the type and amount of bank-side vegetation, and was lowest in fish from areas where the native trees and understorey had been cleared.

'RIVER IMPROVEMENT'

'River improvement' schemes are aimed at controlling erosion, minimising the effects of flooding, and improving the water carrying capacity of streams. In Victoria in 1969, about 2,250 km of rivers and streams (this distance being divided almost equally between coastal streams and those flowing into the Murray) were subject to 'river improvement' (Wharton 1969) and today the areas under the control of river improvement trusts are even more extensive (Conservation Council of Victoria 1977). 'River improvement' activities imply physical modification of streams. They include desnagging of waterways to remove logs and other debris, the removal of standing trees which are likely to fall into rivers and, often, the straightening of a river to make it more like a channel. As pointed out by Rogan (1977), these activities take place without any overall planning or coordination and, in most cases, with little thought of the direct or indirect effects on the aquatic fauna.

The desnagging of rivers removes much of the available cover, particularly for fish such as blackfish which are frequently found amongst debris. Many North American studies, e.g. see those cited by Gunderson (1968), have demonstrated the importance of cover to fish; more fish invariably occur in those sections of river which have the most cover. Desnagging also reduces the number of potential native fish spawning sites. J. S. Lake (1967a) found Murray cod eggs adhering to the inside of a fibro-cement pipe in a pond at the New South Wales Inland Fisheries Research Station at Narrandera, and it seems likely that under natural conditions Murray cod lay eggs within or on logs or other debris on the river bed. This probably is true also for trout cod, which also have adhesive eggs (Cadwallader 1977). Developing blackfish eggs have been found in submerged hollow logs in a natural situation (Jackson 1978) and, although blackfish may also lay eggs beneath and between boulders, logs and other debris may provide the only egg deposition sites in soft-substrate situations. In addition, the removal of debris from river banks and flood plains reduces the number of potential spawning sites which may be used during floods or high-water conditions.

Channelization converts a meandering stream with alternating pools and runs into a straight ditch with continuous runs and high banks. The consequent negative effects on invertebrates and fish are widely recognised (see Schneberger & Funk 1971). One example of the effects of channelization on aquatic fauna is provided by the work of Moyle (1976a) in California. In this study it was found that the invertebrate biomass and the fish biomass in channelized sections of a stream were less than one third of the invertebrate biomass and the fish biomass in unchannelized sections. The invertebrate species composition of channelized and unchannelized sections was also different.

POLLUTION

Water pollution may be defined as 'a significant and deleterious change in the natural character of a water resulting from the addition of material or heat by man' (Williams 1969). The range of pollutants is vast (Bayly & Williams 1973, Connell 1974), but the main water-pollution problems in Australia relate to sewage, industrial effluents and salinity (Frith 1973). Jones (1964) reviewed the effects of river pollution on fish, with particular reference to North America and Europe, but, although there are some records of isolated fish kills produced by gross pollution, there is very little published material on the sub-lethal or otherwise long-term effects of pollution on the native fish of the Murray-Darling Basin.

The most comprehensive study of water pollution in the Murray-Darling Basin is probably that of Weatherley *et al.* (1967) on zinc pollution in the Molonglo River. At Captains Flat on the upper Molonglo River, zinc, copper and lead mining has resulted in extensive tailings, rich in zinc, being distributed for about 15 km along the river banks. Zinc entered the river from these tailings and from mine drainage water and caused the reduction or disappearance of whole components of the normal stream fauna (as judged by comparison with neighbouring streams) for about 40 km downstream. Molluscs, crustaceans, plecopterans and fish were very poorly represented in this stretch. Zinc not only poisons fish and their food organisms directly, but it also destroys the epilithic algae which serve to cement the substrate together. A marked instability of the substrate is characteristic of the badly polluted stretches of the river. P. S. Lake (1973) doubts whether the Molonglo River will ever adequately recover from the pollution and points out that, as a general rule, ecosystems that have been damaged by heavy metal pollution very rarely return to their original condition. It is

significant that where the Queanbeyan River enters the Molonglo River there is a relatively normal flora and fauna because of the dilution of the polluted water.

Agricultural sprays have also taken their toll. Many of these sprays contain D.D.T. which under certain conditions is lethal to some fish in extremely low concentrations (Jones 1964). Such insecticides are a danger to fish even when used in sub-lethal concentrations because, as pointed out by Pollard & Scott (1966), fish food organisms can store insecticide residues and pass on large amounts to fish. In Victoria, Butcher (1965) reported that it had not been possible to find any freshwater fish which were entirely free of insecticide residues, despite the fact that collections were made in some very isolated areas. Fish from the Namoi region of New South Wales have also been found to contain from 0.1 to 3.3 ppm of D.D.T. residues (Connell 1974). The sub-lethal effects of pollutants are often subtle and may require long-term monitoring if they are to be understood. Kleerekoper (1976) has suggested that general locomotory behaviour and orientational response to environmental stimuli may be affected, with consequent adverse effects on predator-avoidance responses. Vigour, the ability to reproduce, and the development and survival of young fish may also be affected (Butcher 1965, Weis & Weis 1977).

Fish kills have occurred in Victoria after agricultural application of Lindane, Aqualin, and Endrin (Connell 1974). Some of these kills have occurred after the spraying of tobacco crops adjacent to streams (Butcher 1965). Several instances of fish mortality due to the use of insecticides to control mosquitos have been reported, and algacides used for clearing weeds from irrigation ditches have also caused fish kills (Pollard & Scott 1966).

Enormous fish kills occurred in the Murray River after the first releases of water from Hume Weir. These kills have been attributed to the large amounts of eucalyptus oil and ash carried downstream. The later use of copper sulphate (between 24 and 35.5 tons per summer between 1929 and 1934) to control algal growth in the weir also caused fish kills (Cadwallader 1977).

Some inland rivers were always to some extent saline, but since European settlement and the development of agriculture the salinity of some rivers has increased greatly (Bonython & Frith 1974). To date, there is no demonstrable evidence of any significant effect of salinity on the fish of the Murray-Darling Basin. Indeed, as pointed out by Butcher (1973), it is likely that during the course of their evolution many animals associated with the Murray have had to contend with large natural fluctuations in salinity. In a study of the occurrence of fish in saline lakes in Victoria, Chessman & Williams (1974) found that many native species, e.g. smelt, big-headed gudgeon, western carp gudgeon, pigmy perch, hardyhead and flat-headed galaxias, all of which also occur in the Murray-Darling System, can tolerate salinities greater than 3,000 ppm. In addition, the normally catadromous common galaxias, *Galaxias maculatus*, which occurs in the lower reaches of the Murray, has been found in waters with a salinity as high as about 49,000 ppm (Chessman & Williams 1975).

INTRODUCED FISH

There are nine self-maintaining species of introduced fish in the Murray-Darling Basin (Table 3). The history of their introduction and acclimatisation, dating back to 1864, has been reasonably well documented, e.g., see Nicols (1882), Wilson (1879), Dannevig (1904), Roughley (1951), Arentz (1966), Butcher (1967) and Weatherley and J. S. Lake (1967). In addition, Atlantic salmon, *Salmo salar* L., were recently liberated in the Goodradigbee drainage of Burrinjuk Dam (Francois 1965), but they do not appear to have established themselves and the New South Wales State Fisheries Atlantic salmon effort is now centred on Lake Jindabyne. Also, brook trout, *Salvelinus fontinalis* (Mitchill), have recently been liberated in some high-country tributaries of the Murray in New South Wales and are thought to have established themselves in some areas (New South Wales State Fisheries, pers. comm.).

TABLE 3
INTRODUCED FISH OF THE MURRAY-DARLING RIVER SYSTEM

Family	*Species*	*Common nam[e]*
Salmonidae	*Salmo trutta* (Linnaeus)	Brown trout
	Salmo gairdneri (Richardson)	Rainbow trout
Percidae	*Perca fluviatilis* (Linnaeus)	European perc[h] (Redfin)
Cyprinidae	*Cyprinus carpio* (Linnaeus)	European carp
	Carassius carassius (Linnaeus)	Crucian carp
	Carassius auratus (Linnaeus)	Goldfish
	Tinca tinca (Linnaeus)	Tench
	Rutilus rutilus (Linnaeus)	Roach
Poeciliidae	*Gambusia affinis* (Baird and Girard)	Mosquito fish

In the Murray-Darling Basin, both brown and rainbow trout typically occur in high-country rivers and streams, especially above 600 m altitude. However, where there is a rapid fall of cold water from high altitudes they are found down to below 300 m. Their range is extended further by the discharge of cold water from large water storages. Both species are found occasionally along the whole length of the Murrumbidgee, in the Murray downstream to beyond the border of South Australia, and as far downstream as Brewarrina on the Darling. The downstream limits of their range are controlled by high water temperatures and also, to some extent, lack of suitable spawning areas. However, liberations of fish from the State Fish Hatcheries of New South Wales and Victoria often maintain trout populations in marginal habitats. In general, in the Murray-Darling System trout occur above 600 m altitude in all of the main tributaries of the McIntyre, Gwydir, Namoi, Macquarie, Lachlan, Murrumbidgee and Murray (Weatherley & J. S. Lake 1967).

European perch are widespread and common throughout the major rivers to the west of the Great Dividing Range, except for most of the Darling. They are usually most abundant in still or sluggish water among or near weeds, but when floods occur they may be distributed uniformly throughout the rivers (Weatherley 1963, Weatherley & J. S. Lake 1967, Cadwallader 1977).

Tench have a widespread but discontinuous range in the Murray-Darling Basin, occurring mainly in relatively sluggish and weedy river stretches and in lakes. They are common in the swampy regions of the Lachlan River above its confluence with the Murrumbidgee. They do not usually occur in the headwater sections of rivers. According to Weatherley & J. S. Lake (1967), goldfish and crucian carp occur generally throughout the Murray-Darling Basin, though their distribution in high-country areas is rather patchy. They are usually found in the more sluggish rivers and in dams, shallow lakes and lagoons. European carp have been in Australia for many years (Stead 1929), but their spread throughout the Murray-Darling River System has occurred only recently (Wharton 1971). In about 1964-65 they spread from Lake Hawthorn near Mildura along the Murray into South Australia and towards Swan Hill, as well as into the Darling and Murrumbidgee. Their range is now extensive: they have been found in the Kiewa River, above Yarrawonga Weir, downstream as far as the mouth of the Murray and throughout inland New South Wales and into southern Queensland (Apps 1976). Weatherley and J. S. Lake (1967) reported that roach are rarely found in the Murray-Darling System, but they have been found recently in the Eildon Reservoir on the Goulburn River (Cadwallader & Rogan 1977).

Mosquito fish occur throughout the Murray-Darling System, but they are not usually found in the cooler waters of high-country streams; they also avoid rapid waters (Butcher 1967, Weatherley & J. S. Lake 1967).

With few exceptions, information on the effects of introduced fish on the native fish fauna is anecdotal and fragmentary, not only because so little is known about native fish, but also because the effects of introduced fish have been overshadowed by the effects of the great physical changes that have taken place in native fish habitats. There is much overseas evidence of the adverse effects of introduced fish on native fish, e.g. Miller (1961), Regier (1968), Zaret & Paine (1973), Zaret (1974) and Moyle (1976b), and *a priori* it must be assumed that the introduction of any new species will have repercussions as far as the native fauna is concerned. To date, the incessant liberation of trout by the State fisheries agencies of New South Wales and Victoria has been the most prevalent form of species pollution in the Murray-Darling River System. As in Tasmania and New Zealand, trout have been liberated into almost all waters thought to be suitable for them, but unfortunately in most instances little information is available on the composition of the native fauna before the first trout introductions were made.

Trout have fragmented the range of some species of galaxiids into a number of small isolated populations. For example, R. Frankenberg (1966) found that in the headwaters of the Kiewa River on the Bogong High Plains brown trout occupy the main body of the stream, while galaxiids are found only in situations inaccessible to trout, such as above waterfalls. A similar situation involving brown trout and *Galaxias olidus* was found in a recent survey of the Seven Creeks River System (Cadwallader unpublished data). In addition, during a survey of all major streams in the Lake Eucumbene catchment, Tilzey (1976) sampled one particular stream over a period which spanned an invasion by rainbow trout. In 1971 the stream contained only *G. olidus*; by 1974 the galaxiids had completely disappeared below a natural barrier to trout, but above the barrier the biomass and population structure of *G. olidus* had not changed greatly after 1971. Historical data for the catchment area suggested that the introduction and subsequent success of trout are primarily

responsible for the present much fragmented galaxiid distribution. Similarly, McDowall (1968) concluded that, although data were not conclusive throughout New Zealand that trout are detrimental to stocks of native fish and other aquatics, 'it is clear that in some localities and for some species, there has been extinction or marked stock reduction of native forms associated with the presence of the introduced trout'.

In a summary of the 'scanty knowledge' of the relationships between the more important (from the angling point of view) indigenous and non-indigenous fish of Australia, Butcher (1967) reported that trout eat small Macquarie perch, trout cod and blackfish. There is also a great overlap in the diets of trout and of these three native species (McKeown 1934, Butcher 1945, Cadwallader unpublished data), whose ranges extend (or once extended) to many waters in which trout have been introduced. In addition to predation and competition for food, it is also likely that trout cod and trout compete for space on the stream bottom. Observations on the behaviour of young (1-6 months old) trout cod in aquaria (Cadwallader unpublished data) indicate that they establish well-defined territories among the boulders and pebbles on the substrate, similar to the territories described by Kalleberg (1958) for young trout.

The food requirements of European perch are similar to those of the larger native species, such as Murray cod and golden perch. In addition, this species is also a voracious predator on smaller fish (Butcher 1945). The annual Melbourne-marketed catches of European perch and 'Murray fish' from the Kerang lakes between 1919 and 1949 (Fig. 4) may perhaps reflect the actual relationships between this introduced competitor-predator and the native fish fauna of the area. Such data must be interpreted with caution, but it appears that when

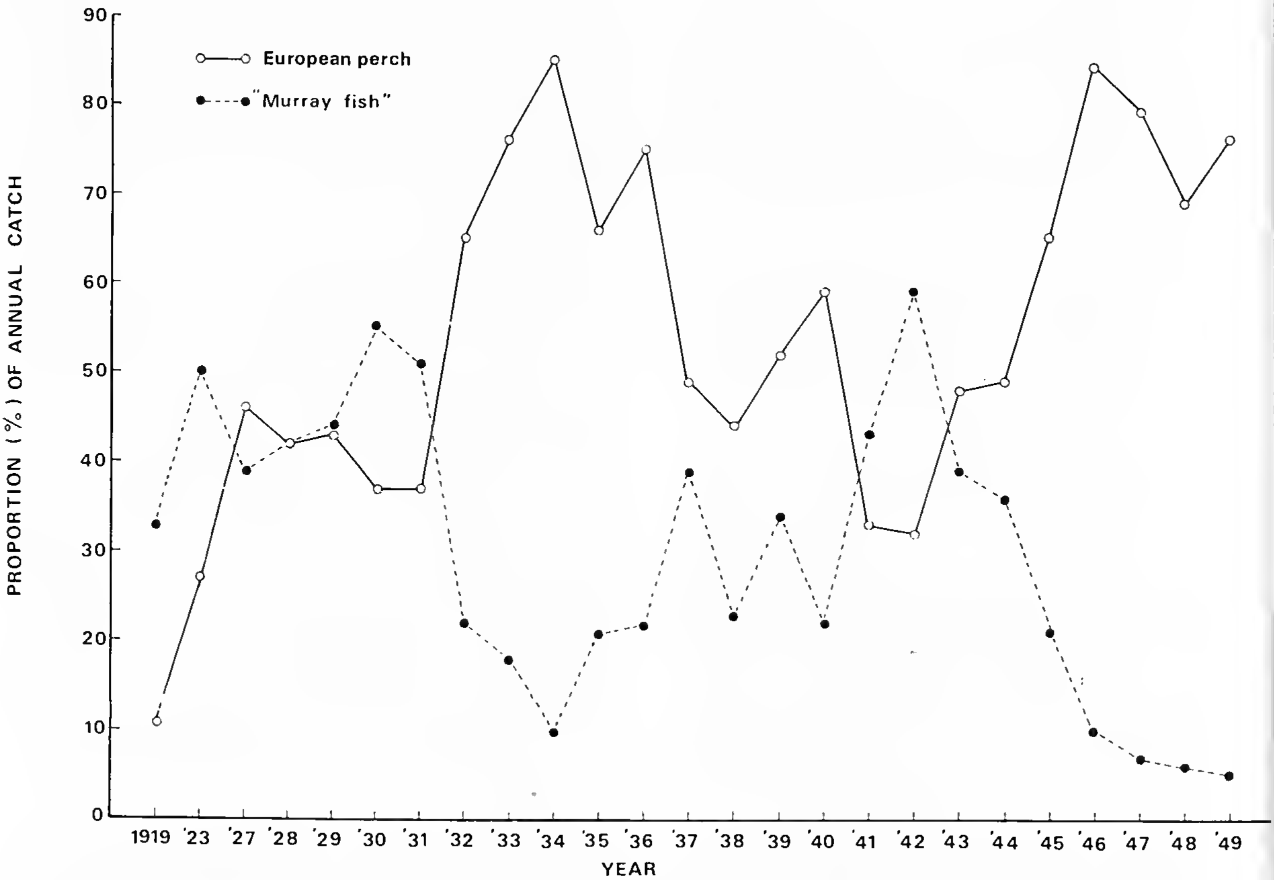

FIG. 4 — Proportion (%) of European perch and 'Murray fish' (includes all native fish, mainly silver perch, golden perch, Murray cod, bony bream and catfish, as well as *Carassius* spp.) in the annual Melbourne-marketed fish catch taken in the Kerang Lakes between 1919 and 1949. After Cadwallader (1977).

there was a large population of European perch the 'Murray fish' population was low and did not increase until the European perch population declined, and so on.

The diets of tench, roach, goldfish, crucian carp and European carp overlap those of native fish such as silver perch and, to a lesser extent, Macquarie perch (J. S. Lake 1959, Butcher 1967, Cadwallader & Rogan 1977, Cadwallader unpublished data). As well as feeding on the same foods as both native fish and some of the larger invertebrates which native fish ultimately feed on, European carp may also modify the environment (Butcher 1962). By their feeding and spawning behaviour they destroy weed beds, which provide shelter and food-producing areas for other fish. In addition, their feeding habits may increase the turbidity of the water and disrupt plant growth in warm, slow-flowing waters. In shallow lakes water quality deteriorates markedly and may not be restored until the carp are removed. On the other hand, in rivers and large deep lakes, the effects of carp may not be so pronounced and, in fact, some lakes can carry large populations of carp without showing any signs of deterioration in water quality (Apps 1976). Weatherley and J. S. Lake (1967) also point out that many rivers inhabited by native fish 'are by nature muddy', and that some native fish, such as catfish, do a lot of bottom grubbing, thereby also contributing to the turbidity.

Myers (1965) pointed out the dangers of introducing mosquito fish, *Gambusia affinis*, into areas where it does not occur naturally. He noted that almost everywhere that *Gambusia* had been introduced it had gradually eliminated most or all of the smaller native species of fish and had also often taken a heavy toll of the young of large fish species. In the Seven Creeks River System, the diet of *G. affinis* was found to be very similar to that of smelt (Cadwallader unpublished data). A related species, *Gambusia dominicensis* Regan, has apparently penetrated into water holes in central Australia, where it threatens the existence of the rare desert goby, *Chlamydogobius eremius* (Zeitz) (Connell 1974). Stephanides (1964) reported the wholesale destruction by *G. affinis* of the Entomostraca and aquatic insects of a small Corfu lake, and Hurlbert *et al.* (1972) found that in artificial ponds *G. affinis* greatly reduced the rotifer, crustacean and insect populations with a consequent extraordinary development of phytoplankton.

Apart from competition and predation by introduced fish on native species, the introduction of foreign fish diseases may have severe effects on native fish. It is extremely fortunate that until now many of the serious fish diseases do not appear to have been introduced, although intensive fish culture has not yet developed to the extent which would readily indicate their presence (Ashburner 1976). In the early days of fish introductions, eggs and fry were subjected to a relatively effective quarantine period because of the distance of Australia from the source of supply of these fish; diseased eggs and fry died at sea. With the advent of air transport the time factor has been eliminated and it is possible that diseases may have entered Australia in recent years. For example, the disease mycobacteriosis has recently been found in quinnat salmon, *Oncorhynchus tshawytscha* (Walbaum), imported from Oregon, U.S.A., in 1966 (Ashburner 1977).

The large number of fish species currently being imported into Australia as part of the aquarium fish trade (McKay 1977) also presents a serious threat to the native fish fauna of the Murray-Darling System.

OVERFISHING

Overfishing of native fish stocks by commercial fishermen has probably contributed to their decline in certain areas of the Murray-Darling System (Roughley 1951). In addition, in 1959 and 1960 the spawning migration of Macquarie perch from Eildon Reservoir into the inflowing Jamieson and Goulburn Rivers coincided with the opening of the angling season, and the total catch of Macquarie perch from these rivers during the opening week of each season was estimated at 2-3 tonnes of fish. Such catches must have had a deleterious effect on the Macquarie perch stocks, particularly in conjunction with the illegal fishing which is known to have occurred when the migration occurred in the closed season (Cadwallader & Rogan 1977).

In conclusion, although preservation of the natural aquatic environment received little or no consideration in the early planning for water conservation and land management (Wharton 1969), there is still scope in some areas for controlling or eliminating some of the factors which may further reduce the distribution and abundance of native fish, e.g. by adopting, where possible, water management practices that take into consideration the spawning requirements of native fish, by more rigid control of detrimental forestry and agricultural practices, by curtailing pollution, by preventing the introduction of new species, and by careful consideration of the implications of any further proposed changes to the environment. Considerable further work is required on the

factors affecting the distribution and abundance of native fish, and the results of this work should be used for determining future river management policies.

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21

VEGETATION OF THE ROYAL BOTANIC GARDENS ANNEXE AT CRANBOURNE, VICTORIA

By P. K. GULLAN*

ABSTRACT: The Royal Botanic Gardens Annexe at Cranbourne supports 200 ha of closed-heath, closed-scrub and low closed-forest (*sensu* Specht, 1970). Variation of the floristic composition of the vegetation is mostly continuous along topographic and edaphic gradients, but sharp discontinuities occur where permanent water is at, or close to, the soil surface.

Studies made of regeneration after clearing suggests that if the topsoil is not removed floristic regeneration is complete within 8 years, while structural regeneration may take up to 30 years.

A method for sorting two-way tables for vegetation description is included. This method employs a polythetic, agglomerative, non-hierarchical clustering procedure, with a data editing facility.

INTRODUCTION

The Royal Botanic Gardens Annexe at Cranbourne is approximately 200 ha of undulating land situated in a rural area some 50 km from Melbourne and about 15 km from both Westernport and Port Phillip Bays (Fig. 1). It was purchased by the Botanic Gardens from the Department of the Army in 1969 for the purposes of developing a native plant botanic gardens, a wildflower reserve and an area for biological research. Since the date of purchase developmental activities have been minimal and this study presents information relevant to the present ecology and future management of the Annexe, and lays the groundwork for subsequent biological research.

The first step in this program was to establish the variety, frequency and distribution of the plants contained in the Annexe. This information will become the reference data for future studies on the dynamics of vegetation and animal populations of this area (Braithwaite & Gullan 1978).

SAMPLING METHODS

Raw data for the survey were floristic and structural descriptions of vegetation collected (during 1972) at 168, 5 x 5 m quadrat sample sites. These sample sites were arranged on a regular grid, as recommended by Williams (1971), with intervals of 100 m between sites. All plants (with the exception of fungi) which projected over, or grew within the quadrat area were recorded and each was assigned a value based on a visual estimate of its cover/abundance (Gullan *et al.* 1976). Structural information was based on a simple division of the vegetation into strata, and a visual estimate of the cover for each stratum.

Quadrat sites were located with the aid of a recent (1972) 1 : 10,000 scale black-and-white aerial photograph (Pl. 16, above) with a regular, 1 cm interval grid superimposed on it.

METHODS OF ANALYSIS

The floristic data were analysed with the aid of a technique for sorting two-way tables which incorporates a polythetic, agglomerative, non-hierarchical clustering procedure for both normal and inverse analyses, and an editing procedure for removing uncharacteristic species (i.e. those not indicative of any vegetation group) from the data before the inverse analysis.

This technique, although incorporating a number of procedures previously described in the literature, is original in design and has not been used in vegetation studies before. A complete description of its mode of operation is given in Gullan (1975).

THE CLUSTERING PROCEDURE

The clustering procedure was devised by Carlson (1972) for psychological studies. Clusters are formed so that individuals within a cluster should

*Botany Department, Monash University, Clayton, Victoria 3168.
Present Address: National Herbarium, Birdwood Avenue, South Yarra, Victoria 3141.

be more similar to each other than to any individual outside the cluster. In an unmodified form, however, Carlson found that the resulting classification was trivial. Clusters usually contained three individuals or less and the majority of individuals were not clustered at all. He therefore introduced a heterogeneity parameter into the algorithm so that '. . . an object was no longer required to have all the similarity indices for members of its cluster higher than its similarity indices for non-members. Five percent of these indices could now be exceptional'.

Bradfield (1975) employed the Carlson clustering method in an analysis of vegetation data from the coast of Lake Erie. The analysis was run several times on the same data, but each time with a different heterogeneity level (0, 5, 10, 15 and 20%). This procedure resulted in a series of classifications with successively larger clusters and when these different classifications were presented together the result resembled a conventional hierarchical dendrogram (see Bradfield's 'skyline diagram'), although each level was calculated independently of the others.

For the analysis in this paper a modification to the Carlson technique has been made which requires that a minimum similarity between any two members of a cluster be specified. This avoids the problem of an individual joining a cluster, for which it has no strong affinity, simply because it is very dissimilar to all individuals outside the cluster.

Because the Carlson technique can be executed at different levels, the relationships between clusters can be shown at least as well as with hierarchical dendrograms, and as each level is calculated separately, the calculations can be made for as many levels as required. This latter property, found partially in divisive systems but absent from hierarchical, agglomerative systems, is useful when computer facilities are limiting. This property is also useful for sorting two-way tables, particularly when choosing character species for an inverse analysis.

Similarity Coefficient

The Carlson clustering procedure operates entirely on a matrix of similarity values generated prior to the analysis. In this paper the so-called

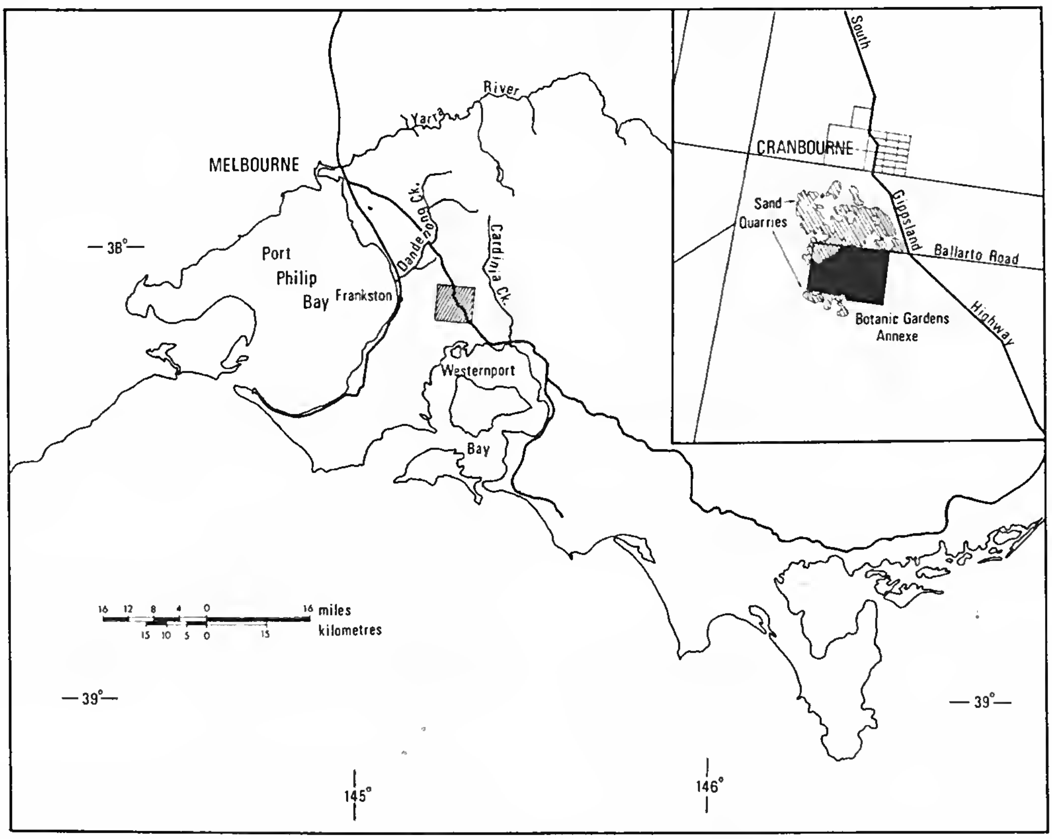


Fig. 1 — Locality map of Cranbourne Annexe. Inset is an enlargement of the hatched area on main map.

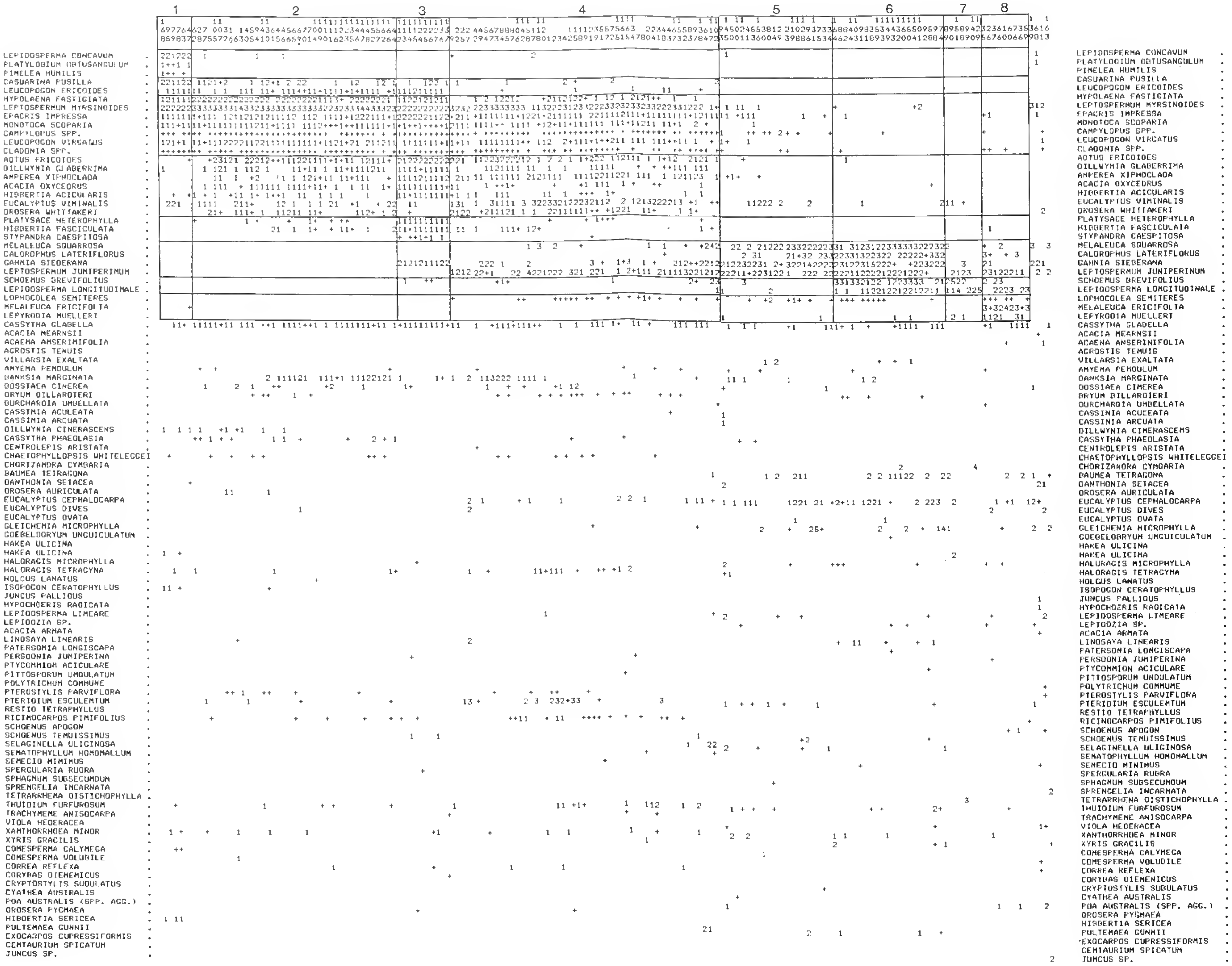


FIG. 2 — Two-way table of 168 quadrats from the Cranbourne Annexe. Vertical lines divide data into quadrat groups, horizontal lines delineate species groups.

'quasi-metric' (Williams & Dale 1965) Jaccard coefficient (Jaccard 1908) was used to create a similarity matrix.

The Jaccard is favoured in this analysis because of its ease of calculation and the straight forward concept of similarity that it conveys.

The similarity matrix takes into account only presence/absence information. Cover/abundance symbols are used simply to compare the variation of plant performance between quadrats, after the analysis is complete. This choice was made because the most useful aspect of two-way tables is their ability to give a visual impression of group composition and the interrelationships between groups. This impression is strongest when adjacent groups differ qualitatively rather than in the changing quantity of species which they share. The analysis thereby produces the most distinctive groups on a two-way table.

Inverse Analysis

In most attempts at inverse analysis a strategy identical to that used for the normal analysis has been employed. However the structure of inverse data is quite different from the normal data set, particularly with reference to species distribution. There is usually a much greater variation in the number of quadrats in which a species may occur than variation in the number of species in a quadrat. An inverse analysis is therefore often confused by the presence of species that occur only a few times, or by those that appear to be distributed randomly.

Austin and Grieg-Smith (1968) have suggested that in some, if not most cases, less than a third of the species in a data set are necessary to demonstrate the major trends in an ordination. Similarly Orloci and Mukkatu (1973) have used a similar premise to define criteria by which species can be ignored in data collection.

In the analysis described in this paper 70% of species were removed from the data set before the inverse analysis. The criterion for removal of these species is based on their frequency of occurrence in clusters of quadrats formed by the normal analysis. If a species occurs in less than N% of the quadrats of *any* cluster then it is left out of the inverse analysis. N is chosen by the analyst and provides a third means by which he may control the heterogeneity of the classification.

The components of the table sorting procedure described above have been incorporated into a single computer program (called MAGIC, Gullan 1975). The clustering part of the program is a modified version of CARLS/CLUST, a program written in FORTRAN IV by Carlson (1972).

Hand Sorting

When the Carlson clustering procedure is run using several heterogeneity levels (Bradfield 1975, Gullan 1975) the species and quadrats can be ordered extremely well and intergroup relationships are demonstrated effectively. However, this process is rather lengthy (both computationally and manually) and in the program MAGIC a single heterogeneity level only has been chosen. This means that although the most similar species and quadrats are placed together in clusters, the clusters themselves are not ordered. The sorting of these clusters must be carried out, by hand, after the analysis, when a second table is printed (using a table printing program modified from ZUMONT/PRINT, Gullan *et al.* 1976) in which the groups are rearranged and any obvious misclassifications corrected.

THE TWO-WAY TABLE AND ITS INTERPRETATION

The floristic data have been divided into *eight* groups, by the above procedure. These are described below.

Group 1: Characteristically a low open vegetation (1 m or less) with scattered, mallee-form* *Eucalyptus viminalis* (3 to 4 m), Group 1 is confined to exposed hilltops where A1 horizons of the soil are shallow (Table 3). A number of species occur in this group that grow nowhere else in the Annexe. Most of these plants are small herbs or shrubs less than 50 cm high, often with a creeping, scrambling or prostrate habit (e.g. *Platylobium obtusangulum, Goodenia geniculata, Drosera planchonii, Lepidosperma concavum*).

Group 2: Group 2 is slightly taller (1 to 2 m) and denser vegetation than Group 1 with more abundant and larger (up to 7 m) eucalypts. In this group *Leptospermum myrsinoides* is generally more abundant than in other groups although it does not grow as tall here as it does in Group 4. This group is distinguished from Group 1 floristically by a greater species richness (Fig. 2), although most of these species are physiognomically very similar (most are small-leafed, sclerophyllous shrubs).

Group 3: This group is confined to a single area of approximately 18 ha near the northern boundary of the Annexe. It is physiognomically very similar to Group 1 but floristically much more closely related

*(All vascular plant nomenclature according to Willis 1962, 1972).

TABLE 1.

DESCRIPTION OF THE STRUCTURE AND FLORISTIC COMPOSITION OF THE VEGETATION.

Species names are in the order that they appear on the two-way table.

In Groups, all species with less than 50% frequency are ignored, as are species considered characteristic of the community.

Since Groups 7 and 8 are regarded as having full community status, structural descriptions for them are included.

COMMUNITY 1.

STRUCTURAL DESCRIPTION.

Tree Layer: Sparse (+) to dense (3) canopy of *Eucalyptus viminalis*, heights ranging from 4 to 12 m.

Shrub Layer: Dense cover of sclerophyllous shrubs (up to 100% cover), predominated by *Leptospermum myrsinoides* (50 cm to 3 m high).

Ground Layer: Mat of lichens (*Cladonia* spp. and *Cladia aggregata*) and mosses (*Campylopus* spp.) interspersed with locally abundant *Drosera whittakeri* and *Pterostylis parviflora* (in late winter to early spring).

Soil Type: Podzol.

CHARACTERISTIC SPECIES OF THE COMMUNITY

Species	Frequency
Leptospermum myrsinoides	100%
Epacris impressa	98%
Hypolaena fastigiata	82%
Monotoca scoparia	93%
Leucopogon virgatus	90%
Campylopus spp.	90%
Cladonia spp.	91%

GROUP 1.

Common Species	Frequency
Lepidosperma concavum	100%
Platylobium obtusangulum	85%
Pimelea humilis	66%
Casuarina pusilla	100%
Leucopogon ericoides	95%
Eucalyptus viminalis	50%
Dillwynia cinerascens	50%

GROUP 2.

Common Species	Frequency
Casuarina pusilla	51%
Leucopogon ericoides	75%
Aotus ericoides	80%
Dillwynia glaberrima	62%
Amperea xiphoclada	61%
Acacia oxycedrus	62%
Eucalyptus viminalis	51%
Drosera whittakeri	56%
Cassytha glabella	82%
Banksia marginata	51%

GROUP 3.

Common Species	Frequency
Casuarina pusilla	50%
Aotus ericoides	100%
Dillwynia glaberrima	100%
Amperea xiphoclada	100%
Acacia oxycedrus	100%
Hibbertia acicularis	100%
Platysace heterophylla	100%
Hibbertia fasciculata	100%
Stypandra caespitosa	70%
Gahnia sieberana	100%
Cassytha glabella	100%

GROUP 4.

Common Species	Frequency
Aotus ericoides	75%
Dillwynia glaberrima	53%
Amperea xiphoclada	80%
Eucalyptus viminalis	78%
Drosera whittakeri	70%
Leptospermum juniperinum	78%
Cassytha glabella	57%

COMMUNITY 2.

STRUCTURAL DESCRIPTION.

Tree Layer: Sparse to dense canopy of *Eucalyptus cephalocarpa* from 10 to 12 m.

Shrub Layer: Dense cover of *Melaleuca squarrosa* and *Leptospermum juniperinum*, from 2 to 7 m high.

Ground Layer: Open, with occasional liverwort ground cover to dense swards of sedges 50 cm to 2 m high.

Soil Type: Humus podzol.

CHARACTERISTIC SPECIES OF THE COMMUNITY

Species	Frequency
Melaleuca squarrosa	90%
Gahnia sieberana	92%
Leptospermum juniperinum	85%

GROUP 5.

Common Species	Frequency
Eucalyptus cephalocarpa	59%

GROUP 6.

Common Species	Frequency
Calorophus lateriflorus	90%
Schoenus brevifolius	85%
Lepidosperma longitudinale	65%
Cassytha glabella	50%

GROUP 7.

STRUCTURAL DESCRIPTION

Tree Layer: Absent.

Shrub Layer: Occasional small (less than 2 m) *Leptospermum juniperinum*.

Ground Layer: Dense sward of sedges (up to 100% cover).

Soil Type: Humus podzol.

CHARACTERISTIC SPECIES OF THE GROUP

Species	Frequency
Leptospermum juniperinum	70%
Schoenus brevifolius	70%
Lepidosperma longitudinale	85%

GROUP 8.

STRUCTURAL DESCRIPTION

Tree Layer: Very infrequent occurrence of *Eucalyptus cephalocarpa* or *Eucalyptus ovata*. Generally absent.

Shrub Layer: Dense *Melaleuca ericifolia* thickets (3–8 m), interspersed with slightly smaller *Leptospermum juniperinum*.

Ground Layer: Fairly dense cover of sedges and rushes, and mats of *Lophocolea semiteres* (Liverwort) on the leaf litter and bark.

Soil Type: Humic gley.

CHARACTERISTIC SPECIES OF THE GROUP

Species	Frequency
Leptospermum juniperinum	89%
Lepidosperma longitudinale	66%
Lophocolea semiteres	77%
Melaleuca ericifolia	100%
Cassytha glabella	66%
Lepyrodia muelleri	66%

to Group 2. The land on which this group is found was cleared of vegetation in 1968 and prior to this time probably supported Group 2 vegetation. This was deduced from examination of pre-1968 (Pl. 16, below) aerial photographs and the fact that almost the entire area is at present surrounded by Group 2 vegetation. Regeneration is not yet complete but it is advanced enough to demonstrate the similarities between this area and Group 2. Notable differences from Group 2 are the absence of *Eucalyptus viminalis* (seedling establishment is apparently very slow) and *Drosera whittakeri* (this plant appears to favour moist, shaded areas which are rare in Group 3 due to the openness of the young vegetation), the increased abundance of *Hibbertia acicularis, H. fasciculata* and *Epacris impressa* (always indicators of areas recently disturbed in the Annexe), and the presence of *Stypandra caespitosa* (found nowhere else in the Annexe) and *Gahnia sieberana*.

The entire 18 ha area is floristically and physiognomically very uniform, and apart from the differences mentioned above, appears to be developing as Group 2 vegetation.

GROUP 4: This vegetation is found primarily on the lower slopes of the Annexe where the A1 horizons of the soils are deep and organic (Table 3). When it is matûre, Group 4 vegetation supports *Eucalyptus viminalis* and/or *E. cephalocarpa* which are larger (up to 15 m) and more abundant in this group than in Groups 1 to 3. However this is not evident from the floristic information in the two-way table as most of the eucalypts in Group 4 are immature due to clearing activities in the 1960's (Pl. 17, above).

GROUP 5: This vegetation is found primarily in depressions between hills and abuts Group 4 vegetation. As in Group 4 the canopy of *Eucalyptus viminalis* and *E. cephalocarpa* is often absent from this group due to the immaturity of the vegetation, but in areas where clearing has not taken place one of these eucalypts (usually *E. cephalocarpa* in Group 5 and *E. viminalis* in Group 4) will form a fairly dense canopy.

The understory of Group 5 is floristically much poorer than that of Groups 2 and 4. Only three species, *Melaleuca squarrosa, Leptospermum juniperinum* and *Gahnia sieberana* are consistent components of Group 5 understory. Thickets formed by the two myrtaceous shrubs often have little more than a thick mat of leaf litter covering the ground beneath them.

GROUP 6: This vegetation grows in wetter depressions than Group 5 and differs from that group in having a more open eucalypt canopy (again this is referring to mature vegetation as this cannot be gathered from the floristic information contained in Fig. 2) and a greater diversity of understory plants, including three monocotyledon species.

GROUP 7: Group 7 is a poorly defined collection of quadrats which have in common a low species

richness and a dominance of one or two species of sedge (*Lepidosperma longitudinale, Cladium tetragonum, Chorizandra cymbaria, Schoenus brevifolius*). All quadrats occur in waterlogged soils (usually 10 — 30 cm of standing water most of the year) and completely lack a tree canopy.

GROUP 8: Group 8 quadrats are found in wet, humic gley soils (Table 2) and are characterised by the presence of *Melaleuca ericifolia* and *Lepyrodia muelleri* (Restionaceae). This vegetation is physiognomically very similar to Group 6 where *M. squarrosa* replaces *M. ericifolia* and *Calorophus lateriflorus* (Restionaceae) replaces *L. muelleri*.

Although the two-way table has been divided into eight groups the most striking feature of the table is its division into two major clusters of species and quadrats. This division is the most important one from the points of view of floristics, physiognomy and environmental variables and represents the two main vegetation communities of the Annexe.

COMMUNITY 1.

Community 1 is made up of Groups 1— 4. Seven species occur commonly (more than 80% presence in every group throughout the community, Table 1), five of which are vascular plants (*Cladonia* is a lichen and *Campylopus* is a moss). Of these five species only *Hypolaena fastigiata* is a monocotyledon, and the rest are small-leafed, sclerophyllous, dicotyledon shrubs. *Leptospermum myrsinoides* is the most prominent of the dicotyledons and forms a significant proportion of the plant biomass in the Annexe. Winkworth (1955) and Jones (1968) calculated that *L. myrsinoides* made up more than 50% of the plant biomass in an area of heath at Frankston, Victoria, which is floristically very similar to that of the Cranbourne Annexe. It varies in size from a small, almost procumbent shrub less than 50 cm high in Group 1, to a fairly large bush (2 to 3 m) forming dense thickets in Group 4. In nearly every quadrat in which it is found *L. myrsinoides* is the most abundant plant (Fig. 2) usually with a cover/abundance value of 2 or 3.

There are noticeable floristic differences between Groups 2 and 4. *Casuarina pusilla* and *Leucopogon ericoides*, common in Groups 1 to 3, are infrequent in Group 4, and *Hibbertia fasciculata, H. acicularis, Acacia oxycedrus* and *Platysace heterophylla* become much less abundant (Table 1). *Gahnia sieberana* and *Leptospermum juniperinum*, found also in Groups 5, 6 and many Group 4 quadrats are almost entirely absent from Group 2.

Before clearing operations began in 1966 the transitions between Groups 1, 2 and 4 were physiognomically (and probably floristically) indistinct (Pl. 17, below). These groups are arbitrary cut-off points on what was a continuum. In 1976 however, much of the Group 4 vegetation was physiognomically similar to that of Group 2 because parts of both were immature and supported young eucalypts. It is to be expected that the continued growth and proliferation of eucalypts in Group 4 will result, not only in a physiognomic transition, but also a change in floristics. In mature stands of Group 4 vegetation surviving in the Annexe at present (e.g. quadrat 153, Fig. 2) some small sclerophyllous shrubs, common in Group 2, are completely absent (those plants described earlier as distinguishing the two groups), whereas they are occasionally found in areas where Group 4 vegetation is immature and the eucalypt canopy is sparse.

COMMUNITY 2.

The second community, made up of Groups 5 and 6, is characterised by three species, *Melaleuca squarrosa, Leptospermum juniperinum* and *Gahnia sieberana*, which occur in over 90% of the quadrats of these two groups. The first two of these species form the main structural components of this community and grow in dense thickets up to 7 m high.

Like Groups 4 and 2, Groups 5 and 6 are not sharply distinct floristically or physiognomically and have been defined by an artificial division on a continuum. The transition from Group 1 to Group 6 is one of continuous variation with the exception of the sharp discontinuity between Groups 4 and 5, and four species, *Leptospermum juniperinum, Gahnia sieberana, Eucalyptus viminalis* and *E. cephalocarpa*, occur occasionally in both groups. The distribution of vegetation groups (Fig. 3) closely follows changes in topography of the Annexe (Fig. 4).

SOILS AND VEGETATION

'Cranbourne Sand' (Holmes *et al.* 1940) forms the undulating topography of the Annexe and distinguishes it from the flatter surrounding land. Much of the surrounding landscape is developed over mudstones and sandstones (Fig. 5) which have formed a fairly heavy humic gley (Stace *et al.* 1972) similar to that described by Holmes *et al.* (1940) as 'Narre Clay Loam'.

The two main soil types of the Annexe are podzols and humus podzols. The podzols are confined primarily to the tops and sides of hills, and the humus podzols are found in the depressions

TABLE 2.

DESCRIPTIONS OF MAJOR SOIL TYPES

Cranbourne Sand: Podzol.

A0	1–3 cm	Fairly dry undecomposed leaf litter. Often crust of lichens and moss.
A1	5–40 cm	Grey to dark grey sandy loam. Fairly high organic content.
A2	40–70 cm	Grey to very light grey sand. Very low in organic matter.
B1	70–75 cm	Thin, dark brown to black, sand cemented together to form hard-pan but it is easily crumbled by hand.
B2	75 cm+	Yellow to orange sand. No organic material except where long roots form pipes through it. Sometimes very deep (8 m or more).

Humus Podzol

A0	1– 5 cm	Moist undecomposed leaf litter (mainly *Leptospermum juniperinum* and *Melaleuca squarrosa*).
A1	5–70 cm	Dark brown very organic loam (almost a peat) with fairly coarse (0.5 mm) sand grains in it. Often water logged almost to the surface. Forms a liquid mud.
A2	70–130 cm	Light grey, sometimes mottled with orange. No investigation to any greater depth because of water table.

Narre Clay Loam: Humic Gley

A0	0– 4 cm	Fairly dense undecomposed leaf litter.
A1	4–25 cm	Dark grey clay-loam with some orange mottling. Friable.
A2	25–65 cm	Light grey clay with orange mottling. Usually wet and slightly sticky.
B1	65–77 cm	Dense grey clay. Very sticky and wet.
B2	77 cm+	Dense red-orange and grey mottled clay. Sometimes fairly large sand grains but always heavy, sticky and waterlogged.

(Table 2). Both soil types are described in the literature as supporting 'heath' (Specht & Rayson 1957, Coaldrake 1961, Groves 1964, Jones 1968) or 'wet heath' (Paton & Hosking 1970). Characteristically both soil types are low in pH, Ca, Mg, K, N and P.

Generally Community 1 vegetation is found on podzols and Community 2 vegetation occurs on humus podzols. The sharp transition from Community 1 to Community 2 occurs across equally abrupt changes from podzol to humus podzol. However, in those areas where Group 4 abuts Group 5 distinctions between the soil types can become difficult.

The humus podzols are usually moist and often waterlogged. The water table is seldom below the top of the A2 horizon and in winter it may rise to the Ao in Group 6, or as high as 50 cm above the soil surface in Group 7. The level of the water table may be related to the presence of a highly impermeable B1 horizon. However no hard 'coffee rock' was encountered beneath humus podzols within the Annexe (although the B horizon was not often reached due to the difficulty of excavation under water), and evidence from mining activities in and around the Annexe suggests that perched water tables are not common. The occurrence of a heavy clay, which underlies the B2 horizons, is probably the most important barrier to downward water movement.

The water table level is likely to be the most significant factor determining vegetation composition. The sharp transition between Communities 1 and 2 is almost certainly related to waterlogging of the A1 horizon of the humus podzols. Gullan (1975) demonstrated that Community 2 and Group 7 plants possess specializations for the transport of atmospheric oxygen to their roots.

Floristic differences between Groups 5, 6 and 7 (the groups found on the humus podzols) correspond to differences in water table level (Table 3a), whereas other soil physical properties (permeability and particle size distribution) are relatively uniform in the humus podzols. However Groups 1, 2 and 4 (the undisturbed groups on podzols) are all found on well aerated soils not subjected to waterlogging, and floristic differences between them are perhaps more closely related to the thickness and permeability of the A1 horizon (Table 3b). The A1 horizon holds almost all of the dead organic material (Findlay 1976) and most of the living plant roots (Jones 1968). In areas where this horizon is thin and fairly dry (Group 1) the plant biomass is low and the vegetation stunted (e.g. *Eucalyptus viminalis* has a mallee habit in Group 1).

TABLE 3.

(a) Depth of water tables for vegetation groups found on humus podzols. Figures are distances above (+) or below (−) the soil surface.

	Min (cm)	*Max (cm)*
Group 5	*−25*	*−80*
Group 6	*− 2*	*−30*
Group 7	*+50*	*− 5*

(b) Range of A1 horizon thickness and permeabilities for podzol groups. Permeability measured using a falling head permeater (Means & Parcher 1964). Measurements taken on soil from the centre of each horizon.

	A1 Thickness (cm)	*Perm. cm sec.$^{-1}$*
Group 1	20 − 25	5 x 10^{-4}
Group 2	30 − 40	1 x 10^{-4}
Group 3	40 − 65	5 x 10^{-5}

Within Community 1 there is a close relationship between topography and the A1 horizon which is thicker and less permeable at lower elevations. Consequently the variation in availability of nutrients and water in the A1 is compounded by the effects of exposure related to topographic variation.

These observations agree with observations on the relationships between soils and vegetation in Europe. Gimingham (1972) emphasizes the importance of drainage in heathland podzols to the development of root systems, and Hansen (1976) demonstrates a close relationship between pH, thickness and field capacity of the 'mor layer' (A1 horizon) and vegetation composition in Danish heaths.

In a few small and isolated areas in the Annexe, a humic gley soil is found which supports Group 8 vegetation. This soil is waterlogged to the surface in winter and is always wet past a depth of about 25 cm.

Plants on the humus podzols are adapted to a wet soil environment and vegetation variation may relate to the effectiveness of plant species in overcoming periodic soil anaerobiosis, and their ability to reproduce under waterlogged conditions. For example, Group 7 plants are mostly rhizomic and reproduce largely vegetatively. Reproduction by seed has obvious limitations in an environment that is almost constantly covered by water. The occasional *Leptospermum juniperinum* in Group 7 may be the result of brief drying out periods where rapidly germinating plants can become established. *L. juniperinum* seeds will often germinate in 36 hours and grow rapidly in the first few weeks (Gullan 1975).

Plants of the humic gley also have special mechanisms for survival on waterlogged soils, but the different floristic composition of Group 8 may relate to the efficiency of plant root penetration of clay or to a better utilization of the generally higher N and P composition of gley soils (Stace *et. al.* 1972).

REGENERATION

The aerial photographic history of the Cranbourne Annexe (Pl. 16, 17) shows clearly that since 1939, large parts of the area have been subjected to clearing (Fig. 6). From 1964 to 1966 vegetation over an area of about 90 ha was cut down, and in 1968 a smaller area (about 18 ha) was cleared. Most of the latter had been cleared four years before. The 1964-66 clearing was a cutting operation and reduced the vegetation to about 10 — 20 cm in height (this height was determined from stereo triplets of aerial photographs using a Zeiss stereomicrometer). Most of the trees in this 90 ha were removed from the Annexe, as few fallen trunks are visible today or can be seen in 1966-68 photographs. An area (about 4 ha) at grid point D 10 (Fig. 3) shows signs of excavation of soil and plants. It is possible that the cropped vegetation was piled here before removal or burning.

The 18 ha area was more drastically disturbed than the larger area. The clearing here resulted in the removal of the top few centimetres of soil as well as the vegetation (Pl. 16, below). The soil and vegetation was pushed into rows to partition the area.

These cleared areas provide an opportunity to monitor regeneration patterns in the Cranbourne vegetation, and to measure growth rates of plants after disturbances.

That much of the vegetation in Groups 4, 5 and 6 was immature was indicated by the evidence that eucalypts in those groups were small, and *M. squarrosa* and *L. juniperinum* in Groups 5 and 6, were often shorter than in other areas. All the quadrats that have been designated immature are found in the hatched area on Fig. 6 cleared between 1964 and 1966. Therefore the eucalypts in these groups were less than 8 years old at the time of the survey, although this is not necessarily true of the other vegetation.

Clearing of the 90 ha area involved only a reduction of the vegetation. Smaller plants, plus the stumps of larger shrubs, probably remained intact (Pl. 17, above). Specht & Rayson (1957) pointed

out that a large majority of heath plants regenerate rapidly after fires, even if the entire above ground portion of the plant is destroyed. The same is true of plants after clearing: if part of the plant above ground is still alive, the regeneration need not begin at the roots. Thus in many cases, particularly in Group 4, the vegetation other than the eucalypts appears quite mature and probably has the same floristic composition as that which it had before clearing. The eucalypts, however, must regenerate from upturned stumps (the trees were pushed down rather than cut, as overturned trunks are present but no cut stumps) or seed, thus their regrowth is slower.

Several areas of Group 2 vegetation were cleared during the 1964-66 period. However Group 2 vegetation is both floristically and physiognomically very uniform. This means that after eight years the vegetation of Group 2 has grown from about 20 cm high to a height indistinguishable from vegetation that is at least 33 years old. It appears that the first few years after clearing produce rapid regrowth of scrub vegetation and then the growth rate slows down considerably.

For Group 4 eight years is obviously insufficient time for regrowth to restore the vegetation to its original state. Aerial photographs show that in most places where quadrats belonging to Group 4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
K								2	4	6	6	4	2	6	6	4	2
J							2	2	2	6	6	7	2	4	6	4	5
I						4	2	3	3	3	6	7	2	4	6	6	5
H						2	2	3	3	3	3	5	7	2	5	6	6
G						2	2	3	3	3	3	2	5	4	5	4	5
F	5	2	1	5	4	6	7	5	6	5	6	2	2	4	2	5	2
E	8	2	1	1	5	6	6	4	4	4	6	4	7	6	7	6	6
			1														
D	8	8	2	2	1	4	2	8	4		2	2	2	4	4	6	5
								4									
C	4	4	2	2	2	1	4	4	5	4	4	5	4	2	2	4	6
B	4	8	4	2	5	5	4	2	5	5	8	8	8	6	4	2	5
A	8	8	4	4	5	2		4	2	4	4	4	4	4	4	5	4
										4	4	4	4	2	2	4	4

FIG. 3 — The distribution of Groups 1–8 in the Cranbourne Annexe. Points represent quadrat sites 100m apart.

Correspondence of grid references to quadrat numbers on the two-way table:

Grid Ref.		Quadrat No.	Grid Ref.		Quadrat No.
Z10 – 17	=	1– 8	G6 – G17	=	110–121
A1 – A17*	=	9– 24	H6 – H17	=	122–133
B1 – B17	=	25– 41	I6 – I17	=	134–145
C1 – C17	=	42– 58	J7 – J17	=	146–156
D1 – D17	=	59– 75	K8 – K17	=	157–166
E1 – E17	=	76– 92	D/C8	=	167
F1 – F17	=	93–109	E/D3	=	168

* Excluding A7

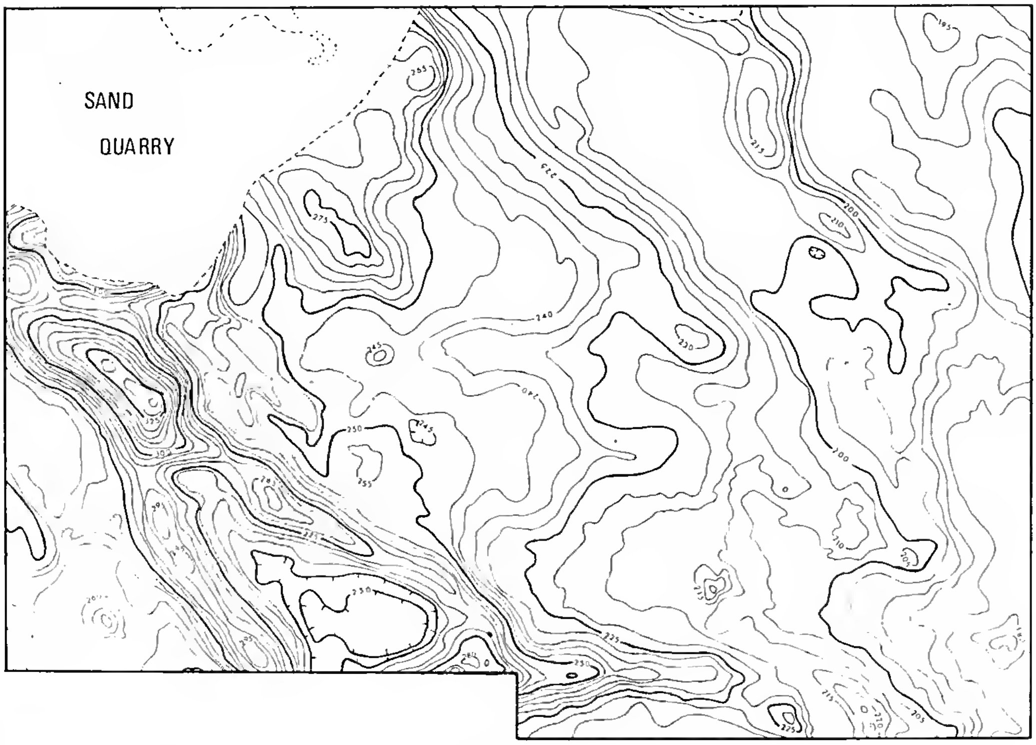


FIG. 4 — Topographic sketch map of the Cranbourne Annexe. Intervals between fine lines are 5 feet (1.5 m).

are found, the vegetation had a complete eucalypt canopy before 1964 (Pl. 17, below). Therefore today Group 4 is physiognomically variable although it is floristically uniform. This variability is artificially induced and is presumably not permanent.

Most quadrat sites in Groups 5 and 6 had fairly continuous eucalypt canopies prior to 1964 and regeneration has not been complete. In all probability Groups 5 and 6 were originally physiognomically similar and differed primarily in the floristics of their ground layer plants. These floristic differences may have been due to the close proximity of the water table to the surface of the soil, as both *Schoenus brevifolius* and *Lepidosperma longitudinale* (the two plants that distinguish Group 5 from 6) are common in swamps where the water table is above the surface. Or they may be due to the slightly less dense, eucalypt canopy in Group 6.

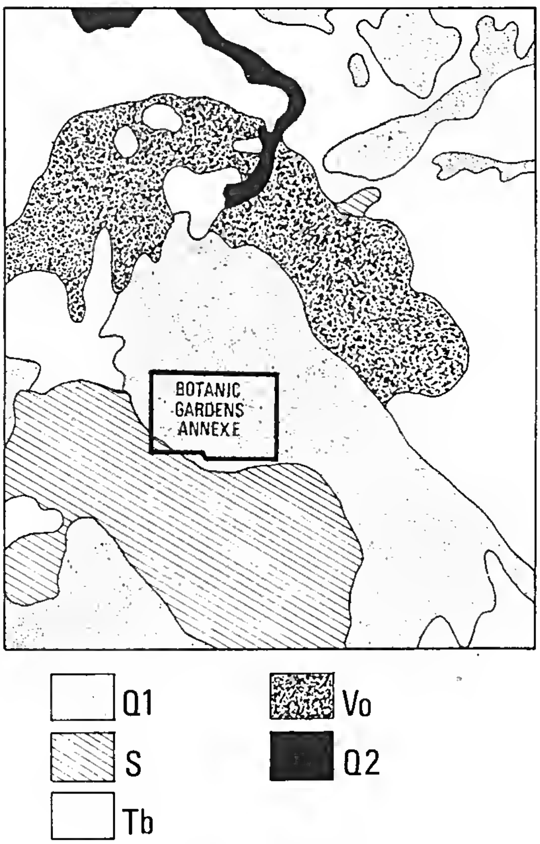


FIG. 5 — Simplified geological map of the Cranbourne Annexe and its surrounds. Vo, Older volcanic (basalt and pyroclastics); Q2, Fluviatile and lacustrine sand, silt, gravel; Tb, Ferruginous sandstone; Q1, Raised beach deposits, beach sands; S, Mudstone, Claystone, Sandstone. (Reproduced from Geological Survey of Victoria, 1:250,000 series, Queenscliff, Sheet No. SJ55–9).

Group 3 vegetation is represented as cross-hatching in Fig. 6 (i.e. cleared in 1964-66 and 1968-69). Removal of some of the upper soil layer (a few cm) makes it different from the other period of clearing documented above. It is probable that the changes incurred by this kind of clearing allowed the germination of *Stypandra caespitosa* and *Gahnia sieberana*, which are plants otherwise foreign to Community 1 vegetation. Nevertheless invasion by some introduced plants such as *Rubus fruticosus*, *Holcus lanatus* and *Hypochoeris radicata*, common outside the study area, was not evident. This may be due to the low nutrient status of the soil (particularly of phosphate) which tends to give heath plants a competitive advantage over most foreign plants (Specht 1963).

In the area surrounding quadrat site D 10 (Fig. 3) most of the sandy horizons have been removed and the introduced plants mentioned above are common, along with several others (see quadrat 68 on two-way table). The total plant cover is also low and has been for many years (see Pl. 16, and 17 above).

Regeneration of vegetation at Cranbourne is dependant upon the type and extent of the original disturbance. When disturbance is restricted to cutting back the vegetation and removing the larger trees, the floristic composition does not appear to change significantly. The vegetation will grow back to its original state with few (if any) alterations. If the vegetation consists of low shrubs without a large tree canopy (such as Groups 1 and 2), regeneration will take only a few years (apparently less than eight), but if it is a woodland, in which the trees are uprooted, (Groups 4, 5 and 6) total regeneration takes much longer (perhaps 30 or 40 years).

When clearing includes removal of the top few cm of soil, regeneration still occurs fairly rapidly (about 1 m in height in the first 4 years) but the relative proportions of its constituent species change slightly (Fig. 2). Floristic changes also

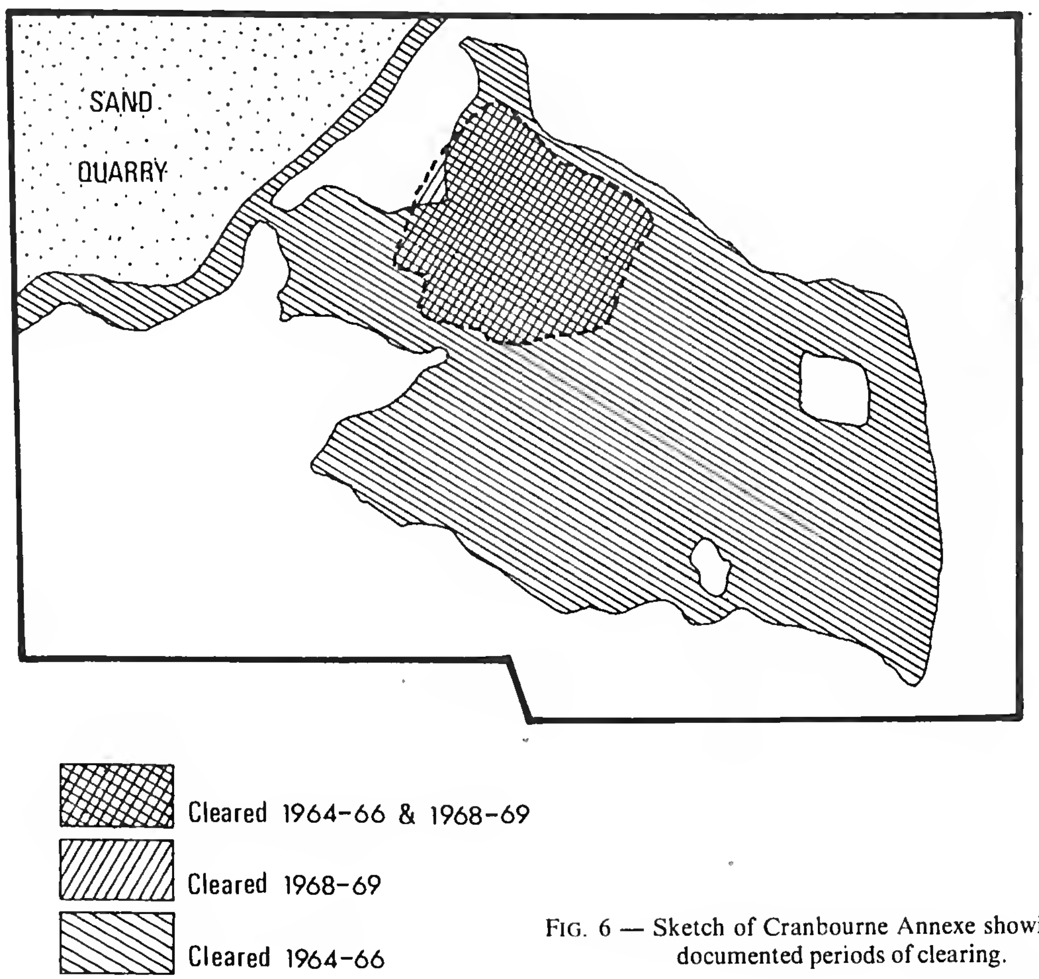


FIG. 6 — Sketch of Cranbourne Annexe showing major documented periods of clearing.

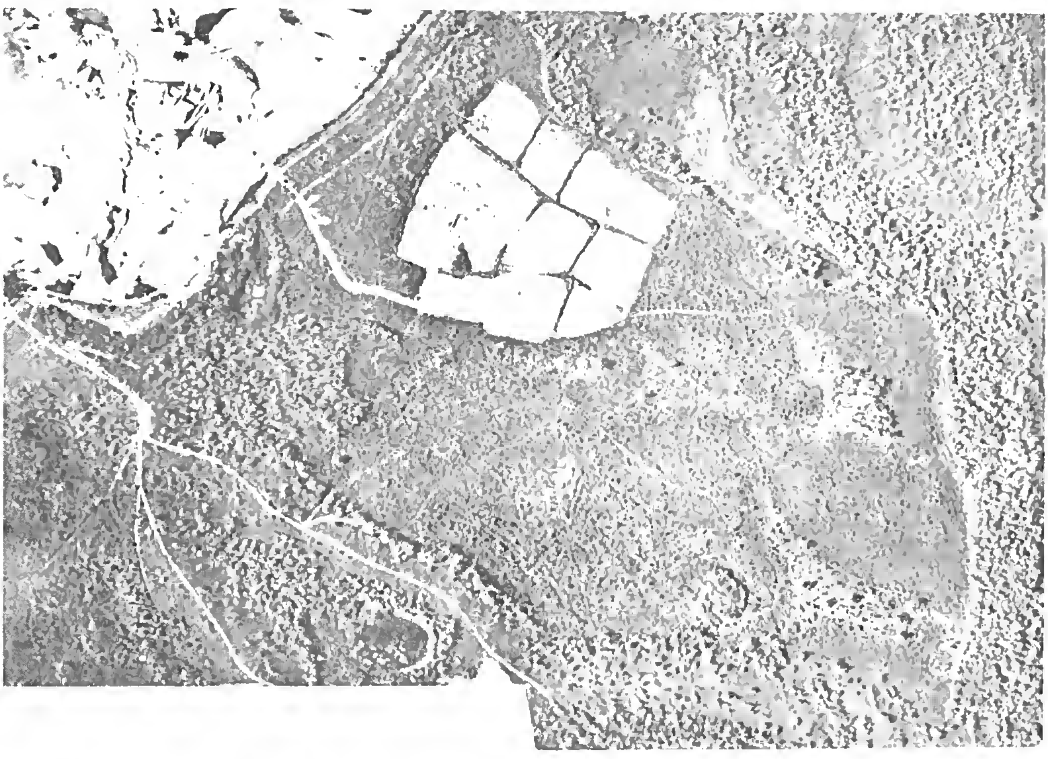
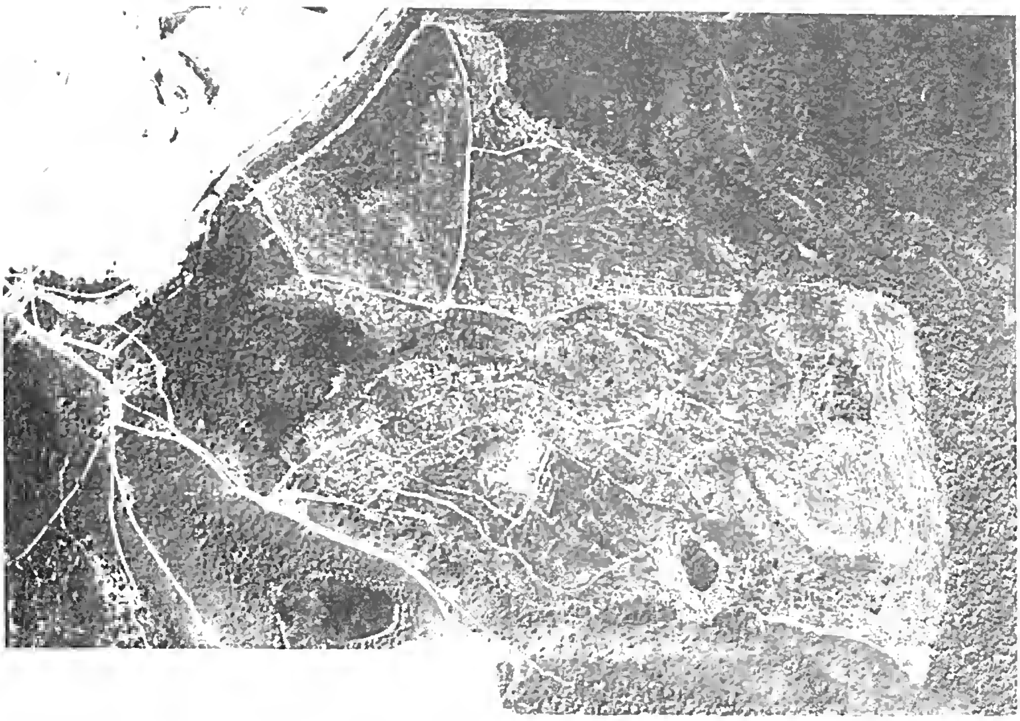


PLATE 16.

(*Above*) 1972 aerial photograph of Annexe. (*Below*) 1968 aerial photograph of Annexe. *Both photographs by courtesy of the Department of Crown Lands and Survey, Melbourne.*



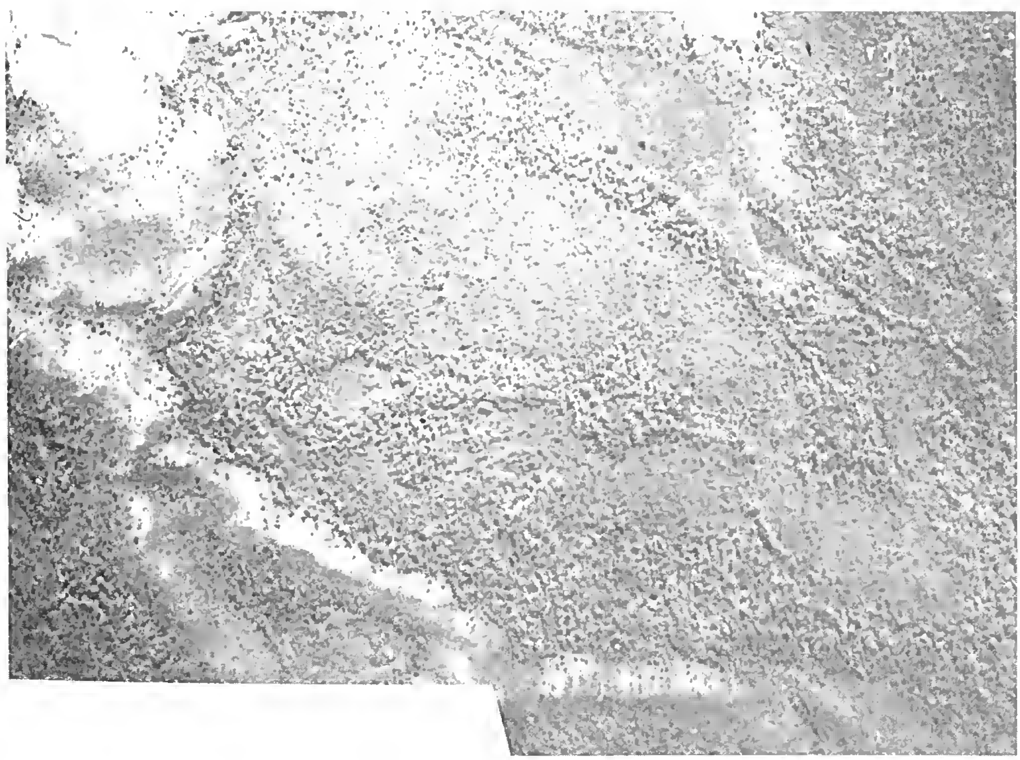


PLATE 17.

(*Above*) 1964 aerial photograph of Annexe. *By courtesy of Crown Lands and Survey, Melbourne.* (*Below*) 1939 aerial photograph of Annexe. *By courtesy of Department of National Mapping, Melbourne.*

occur, e.g. *Drosera* spp. are lost and *Gahnia sieberana* becomes common and conspicuous. However in general the vegetation appears to be the same as before clearing and recognizable after only four years.

Where the soil is excavated to depths that result in roots and seeds being removed from the ground, the original vegetation recovers very slowly. Invasion by foreign, opportunistic plants occurs and the appearance of disturbance is maintained for some time (in the case of D 10 at least eight and perhaps twenty years, and the area still does not appear to be recovering well).

DISCUSSION

The Annexe is in an unstable state at present because of its incomplete regeneration following the three documented periods of disturbance. Information of the kind presented in this paper suggests that the structural and floristic composition of the original vegetation, and the disturbed vegetation, will in 20 years time be almost the same.

The vegetation *communities* (the vegetation units which contain the groups) are considered to have regional significance for 3 reasons. First, they differ significantly in both structural and floristic categories and are found in very different environments. Second, they can be easily distinguished from each other both on the ground and from the air. Finally, the combination of species which characterize the communities (Table 1) has been reported several times on the Mornington Peninsula and Westernport Bay areas (McLennan & Ducker 1954, Winkworth 1955, Groves 1964, Jones 1968, Grant 1974).

For these reasons it is suggested that in most cases the vegetation *communities* defined in this paper are suitable units for mapping purposes whereas the vegetation *groups* are not. The groups may be the result of disturbance factors (Group 3), be difficult to distinguish without detailed floristic

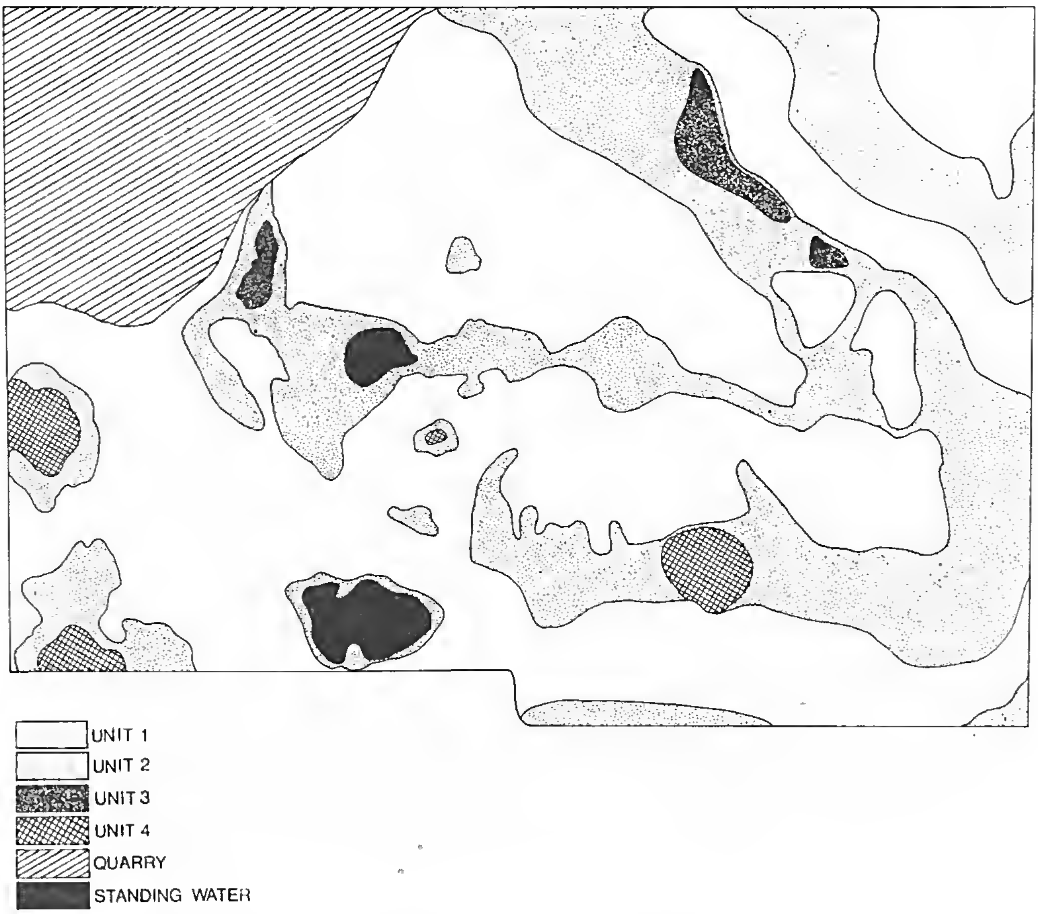


FIG. 7 — Map of the major vegetation communities of the Annexe. Units 1 to 4 are synonymous with those vegetation types described in detail in Table 1. Unit 1 = Community 1 (on Table 1); Unit 2 = Community 2; Unit 3 = Group 7; Unit 4 = Group 8.

information (Groups 2 and 4, Groups 5 and 6) or intergrade imperceptibly into each other (Groups 2 and 4). Despite the difficulties of using these groups for mapping purposes they are useful for fine scale habitat definition of some animals (Braithwaite & Gullan 1978).

Fig. 7 is a map of the major vegetation units of the Annexe. Units 1 and 2 are synonymous with Communities 1 and 2. Unit 3 is synonymous with Group 7 which is floristically heterogeneous, physiognomically uniform and represents a distinct vegetation and habitat type. Unit 4 is synonymous with Group 8, which represents a remnant of vegetation found more commonly outside the Annexe and is floristically and physiognomically distinct from all other vegetation.

Clearly Communities 1 and 2 are the best developed vegetation types of the Annexe. They cover 90% of the land area and their geographical distributions are predictable from topographic data alone. Development of the Annexe for public and scientific use should therefore be directed towards the maintenance, display and study of these two strikingly different habitats.

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22

Drosophila (DIPTERA: DROSOPHILIDAE) OF MELBOURNE VICTORIA, AND SURROUNDING REGIONS

By P. A. PARSONS*

ABSTRACT: The *Drosophila* fauna of suburban/orchard habitats in the Melbourne region (latitude 38°S) differs from neighbouring temperate rain forests. Fermented fruit baiting is successful in the former habitat yielding 5 cosmopolitan species. These 3 are common, and 3 endemic subgenus *Scaptodrosophila* species. The rain forest fauna can be collected only by sweeping; it consists of 10 endemic *Scaptodrosophila* species (of which only *D. fumida* occurs in suburban/orchard habitats) and *D.* (*Sophophora*) *dispar* but no cosmopolitan species. Hence the two faunas are almost entirely different, due to non-overlapping resources utilized. In rain forests at high altitudes where species diversities are low, *D.* (*Scaptodrosophila*) *inornata* dominates almost totally.

Comparisons with the Townsville urban fauna (latitude 20°S) reveal: (1) only the two subgenus *Sophophora* sibling cosmopolitan species *D. melanogaster* and *D. simulans* are in common with Melbourne, (2) species numbers in Townsville are much higher due mainly to a northern *Sophophora* radiation, and (3) there is some species overlap between the Townsville urban and north Queensland rain forest faunas due to the success of fermented fruit baiting in both habitats, in contrast with the discrete Melbourne region habitat differences.

INTRODUCTION

The genus *Drosophila* has speciated widely within Australia and many endemic species occur in natural habitats such as rain forests and undisturbed sedge areas, especially species of the typically Australian subgenus *Scaptodrosophila* (Bock & Parsons 1975, Bock 1976). There are also eight cosmopolitan species defined as occurring in all six of the commonly recognised faunal realms, Nearctic, Neotropical, Palearctic, Ethiopian, Oriental and Australian. Urban collections normally give some of these cosmopolitans using fermented fruit baits; indeed most laboratory studies of *Drosophila* are based on such generalist species. However, *Drosophila* species exploit a much wider variety of microbial degradation products of plant materials (including fungi) than is implied by successful fermented fruit baiting (Carson 1971). Here, the results of fermented fruit baiting in suburban/orchard habitats of the Melbourne region are given, together with collections within 63 km of Melbourne from tree fern gullies where baiting is ineffective; in the latter habitats flies are collected only by sweeping, so resources utilized as assessed by trapping method are completely different for two habitat categories.

COLLECTIONS

Melbourne suburban/orchard collections have been carried out for many years by fermented fruit baiting. (Apart from my own collections, in recent years collections have been carried out by R. M. Cook, J. McDonald, J. A. McKenzie and G. J. Prince and some collection data are in the Ph.D. theses of the latter two persons). Species compositions especially their relative numbers vary widely from day to day and from season to season (McKenzie & Parsons 1974). For qualitative comparisons with the tree fern gully collections, results of all Melbourne populations have been pooled. In Table 1, approximate abundances are indicated by +++ for species representing more than 10% of the total collection, by ++ for those with more than 1%, and by + for those with less than 1%.

Fern gully yields by sweeping are much lower. Actual numbers swept during the summer of 1975/76 are in Table 2, and provide comparative data among localities.

*Australian *Drosophila* Research Unit, Department of Genetics and Human Variation, La Trobe University. Bundoora, Victoria 3083, Australia.

In both cases yields are maximal in summer, which is reasonable, since for southern temperate species resource utilization effectively ceases below about 12°C (Parsons 1978); in fern gullies in particular therefore, flies are unobtainable for many months of the year.

RESULTS AND DISCUSSION

Eight species have been found in the suburban/orchard regions of Melbourne (Table 1), 5 being cosmopolitan and 3 *Scaptodrosophila*. Three cosmopolitan species have not been found in Melbourne, although 2 of subgenus *Drosophila* (*funebris, repleta*) are known from various localities in eastern Australia, but the third of subgenus *Sophophora* (*ananassae*) is known only from north Queensland including Townsville (Table 3). Two species only are common to both cities, the cosmopolitan subgenus *Sophophora* sibling species *D. melanogaster* and *D. simulans*, which have been collected in all large cities in eastern and south-western Australia. These two species are sympatric in many regions, but microecological differences are known especially in the vicinity of wineries, due to the utilization of alcohol as a resource by the former but not the latter species (McKenzie & Parsons 1972). The three additional Melbourne cosmopolitans are *D. busckii* and *D. hydei* which are rare and *D. immigrans* which is common; the latter is the most desiccation sensitive of the three common Melbourne cosmopolitan species (Prince & Parsons 1977) so its absence from the more extreme Townsville conditions (Bock 1978) is not surprising.

Two of the Melbourne *Scaptodrosophila* species, *D. enigma* and *D. lativittata* belong to the *lativittata* complex within the *coracina* species group, all of which are characterized by being attracted to fruit baits (Bock & Parsons 1978a). They are in rain forests from southern New South Wales to southeastern Queensland; presumably they have spread to the Melbourne region with the introduction of orchards. The third species, *D. fumida*, one of two patterned wing *Scaptodrosophila* species known, is widespread in southern Australia, especially orchards (Bock 1976), and has been found in southern Queensland rain forests. In contrast with the *lativittata* complex species, it also occurs rarely in southern rain forests away from fermented fruit resources (Table 2).

In contrast with the 8 Melbourne species listed in Table 1, a total of 14 have been collected (Table 3) by fermented fruit baiting in the urban regions of Townsville (Bock 1978), where, given the harshness of the environment, intuitively only the cosmopolitans *D. melanogaster* and *D. simulans* might have been expected. However, meteorological data show Townsville to have a humid summer providing conditions more permissive for *Drosophila* survival when temperatures are high as compared with drier conditions (Prince & Parsons 1977). Irrespective of the environment, the lower Melbourne species diversity is in any case to be expected, given the more extreme latitude and that

TABLE 1

Drosophila SPECIES COLLECTED BY FERMENTED FRUIT BAITING IN SUBURBAN/ORCHARD AREAS OF THE MELBOURNE REGION.

Subgenus		
Drosophila	*immigrans* Sturtevant	+++
	hydei Sturtevant	+
Dorsilopha	*busckii* Coquillett	+
Sophophora	*melanogaster* Meigen	+++
	simulans Sturtevant	+++
Scaptodrosophila	*enigma* Malloch	+
	lativittata Malloch	++
	fumida Mather	++

TABLE 2

NUMBERS OF FLIES COLLECTED FROM TREE FERN SITES IN THE MELBOURNE REGION.

Localities*	1	2	3	4	5
Distance from Melbourne (km)	41	43	50	63	59
Altitude (m)	320	460	290	590	1130
Subgenus *Sophophora*					
dispar Mather	2	–	–	–	–
Subgenus *Scaptodrosophila*					
inornata Malloch	232	61	39	119	31
collessi Bock	47	–	7	1	–
rhabdote Bock	6	–	–	–	–
obsoleta Malloch	–	–	–	1	–
barkeri Bock	5	–	3	–	–
louisae Parsons and Bock	32	–	11	–	–
notha Bock	1	–	–	–	–
ehrmanae Parsons and Bock	–	–	10	–	–
parsonsi Grossfield	1	–	1	5	–
fumida Mather	1	–	–	–	–
Number of Species	9	1	6	4	1

* 1. Kinglake National Park, Ninks Road; 2. Kinglake National Park, Jehosophat Gully; 3. Badger Creek, near Healesville; 4. Mt. Donna Buang, Cement Creek; 5. Mt. Donna Buang, Summit.

TABLE 3

SPECIES NUMBERS IN MELBOURNE (LATITUDE 38°S) AND TOWNSVILLE (LATITUDE 20°S) REGIONS BY SUBGENUS.

	MELBOURNE –		TOWNSVILLE –
	Suburban Orchard	Treefern Gully	Summarized from Bock (1978)
Drosophila	2	–	2
Dorsilopha	1	–	–
Sophophora	2*	1	9*
Scaptodrosophila	3†	10†	3
Total	8	11	14

* Includes *D. melanogaster* and *D. simulans*.
† Includes *D. fumida*.

the genus *Drosophila* is of tropical origin (Throckmorton 1975). The main fall in species numbers going south is due to the disappearance of 7 of the 9 *Sophophora* species found in Townsville. This is consistent with the presence of a minor north Queensland radiation in this subgenus in rain forests with some species overlapping with Townsville itself. With the exception of isolated flies, the overlap does not, however, extend to cosmopolitan species (Bock 1978, Bock & Parsons 1978b).

In the Melbourne region there are no records of cosmopolitans in temperate rain forests, which is predictable given the absence of fleshy fruits and the ineffectiveness of fermented fruit baiting (Parsons & Bock 1977a). In Table 2 tree fern gully collections by sweeping near Melbourne are given. Of the 10 *Scaptodrosophila* species and one *Sophophoran*, *D. dispar*, only one, *D. fumida* occurs in urban/orchard habitats (see above), showing the two major Melbourne region habitats to have entirely different faunas. This is reasonable since the faunas differ in a major way in resources utilized: the larvae of the rain forest species mine leaves, stems etc. (Bock & Parsons 1978a), not fruits. Therefore the limited overlap between the urban and rain forest faunas in the Townsville region disappears in the Melbourne region because the resources in the south are completely different, and it would be of interest to look at intermediate regions.

The dominance of the *inornata* species group (*inornata, collessi, rhabdote* and *obsoleta* in Table 2) in the south has been already established (Parsons & Bock 1977a). In addition the data show that the dominance of *D. inornata* itself becomes almost total at relatively high altitudes (localities 2,4,5) as compared with relatively low altitudes (localities 1,3) where *barkeri* group species (*barkeri, louisae*) and *bruneipennis* group species (*notha, ehramanae*) occur. The forests at the latter altitudes are floristically more complex than the former, so that as habitats become more marginal by altitude, species diversities fall such that eventually the *inornata* group totally dominates, as also found for western Victorian isolates or latitudinal extremes as in Tasmania (Parsons & Bock 1977a,b). *D. parsonsi*, a rare species not belonging to any of these species groups, is however exceptional in extending from southern Tasmania to North Queensland (at high altitudes), occasionally including rather marginal habitats for *Drosophila* such as locality 4 at an intermediate altitude between 3 and 5 (see Parsons & Bock 1977a for latitudinal data).

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THE VALUE OF HISTORICAL RECORDS: THE WARRNAMBOOL EARTHQUAKE OF JULY 1903

By K. F. McCUE*

ABSTRACT: Historical information drawn mainly from old newspapers was examined to draw up a representative isoseismal map of the larger of the two earthquakes at Warrnambool, Victoria, in 1903. This occurred on July 14. The map was used as a basis for locating the earthquake's epicentre and magnitude. The damage and notable secondary effects such as liquefaction are discussed, in an effort to draw the attention of town planners, engineers and architects to the possible consequences of building in areas of even minor seismicity.

THE EARTHQUAKE

At 2029 local time on the 14th July 1903, an earthquake was widely felt throughout south-western Victoria. Perceptible ground motion did not extend as far east as Melbourne, north as Horsham or west to South Australia and damage was confined to a small area around Warrnambool on the south coast. There was no loss of life or serious injury.

A more detailed examination of the earthquake's effects was made using contemporary newspapers, in particular the Warrnambool *Standard*, Melbourne *Age* and Geelong *Advertiser*. This information was supplemented with entries from some lighthouse keepers' logs to draw up the isoseismal map of Fig. 1. The epicentre suggested by the map is a few kilometres southeast of Warrnambool, which is supported by reports that movement at Warrnambool was a 'thumping up and down' as distinct from the 'undulating' one at Port Fairy, 20 km west.

It has not generally been possible to link Australian earthquakes, especially historical events, with particular faults, although Hills (1975) has associated the 1932 Mornington earthquake with Selwyn's Fault on the eastern side of the Port Phillip Sunkland. Warrnambool is situated near the eastern edge of the Portland Basin about 100 km east of Boutakoff's (1963) Kanawinka line of weakness along the Basin's western edge. This line of weakness has a fine structure of faults rejuvenated in the early Quaternary but not currently seismically active.

Victoria's most recent volcano, Tower Hill, which Gill (1943) recognised to have been of Holocene age, last erupted only five thousand years ago. It is located about twenty km west northwest of the earthquake epicentre but there is no apparent causal relationship between the two.

The earthquake's magnitude has been estimated at ML 5¼ using the approximate equation below (McCue 1977) which is a quasi-empirical formula based on the radius of perceptibility (Rp) measured in km.

$$ML = 1.05 + 1.85 \text{ Log } Rp + 0.8\ Rp/1000$$

This moderate magnitude is supported by the short duration experienced close to the epicentre at Warrnambool, reported variously as between 4 and 12 seconds. There was considerable damage for an earthquake of this magnitude which by comparison is about the same size as the 1954 Adelaide event, Australia's most damaging earthquake, but energy-

TABLE 1
1903 WARRNAMBOOL EARTHQUAKES

Date	*Time* (L.T.)	*Latitude*	*Longitude*	*Maximum Intensity*	Rp	ML
7/4/1903	0952	38°26'S	142°32'E	VII	—	5.0
14/7/1903	2029	38°26'S	142°32'E	VII^{+}	160–170	5.3

*Physics Department, The University of Adelaide, G.P.O. Box 498, Adelaide, South Australia 5001.

wise about 1000 times smaller than the disastrous February 1976 earthquake in central Guatemala which caused 22,000 deaths and left a quarter of the population (1.5 million) homeless. The October 1968 earthquake of magnitude 6.9 (ML) that destroyed the Western Australian wheatbelt town of Meckering (Everingham & Gregson 1970) is rated amongst the largest to have struck within the Australian continent. Victoria's largest earthquake this century, ML 5¾, occurred near Mt. Hotham in May 1966, but caused little or no damage due to its distance from population centres. Several small aftershocks were felt in Warrnambool during the week following the earthquake.

Just three months previously the same area had been severely shaken by another earthquake, the so-called Great Warrnambool Earthquake. Intensity at Warrnambool was assessed at VII (Modified Mercalli Scale) on both occasions, though the damage due to the earlier event was slightly less severe and its felt area smaller. The amplitude of the July event as recorded on the Melbourne seismograph was almost double that of the April earthquake, indicating a difference of about 0.3 in magnitude.

The observation that the duration of the April shock in Warrnambool was longer than that of July may indicate that its focus was further south, but in Table 1 summarising the parameters the same epicentre is assumed.

PAST SEISMIC HISTORY

The earliest report of an earthquake in the district, as noted in a diary of a pioneering resident, occurred in November 1848 (Osburne 1887). At least eight others including the two above occurred in the district between 1900 and 1959 (Underwood 1972), of which the largest was undoubtedly that of July 1903. This brief summary serves to highlight the continuing seismicity of the region despite its

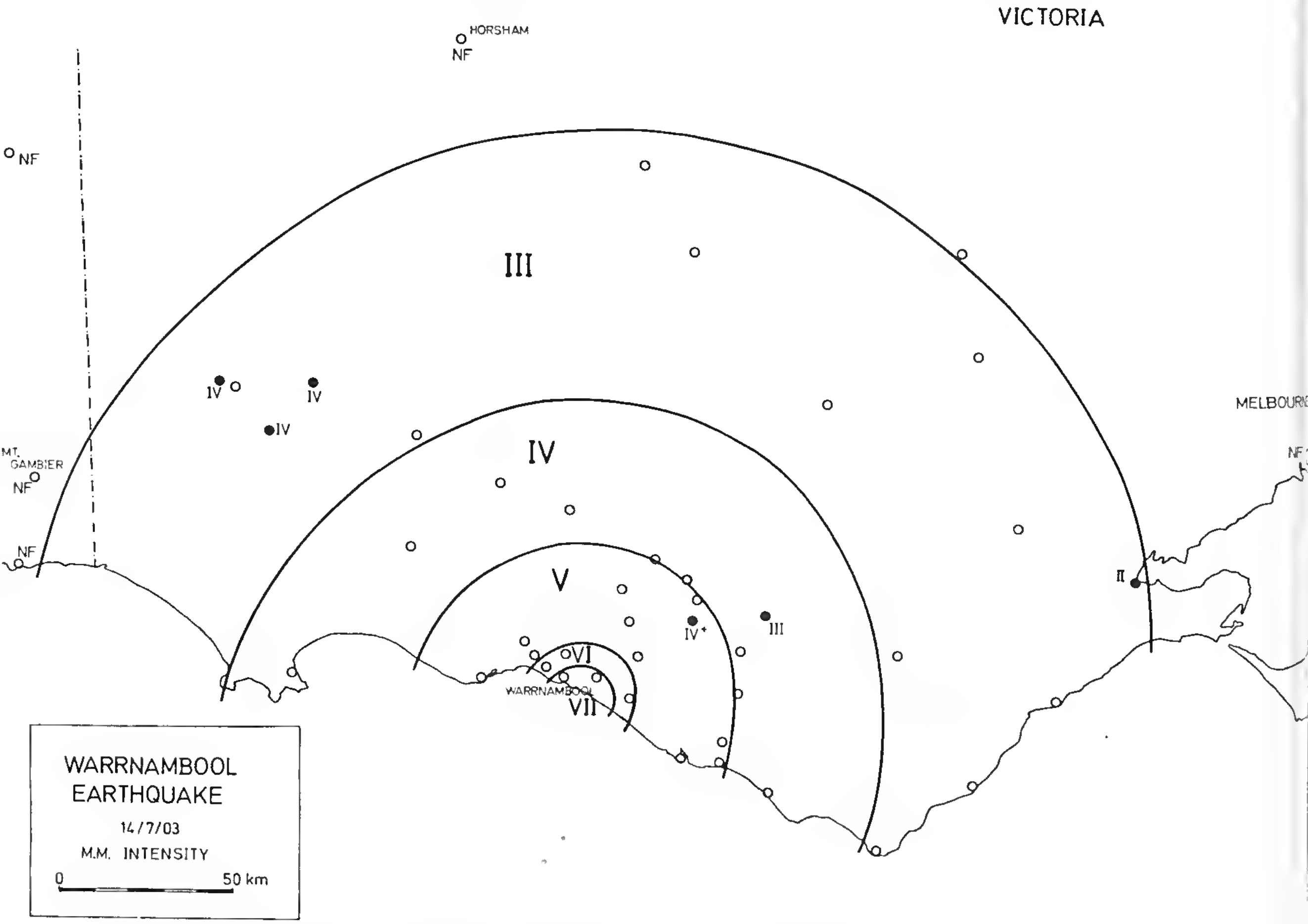

FIG. 1 — Isoseismal Map (Modified Mercalli Intensity) of the July 1903 Warrnambool Earthquake in Victoria. Open circles represent spot intensity values within the labelled range.

PLATE 18

(*Above*) Presbyterian Church after the first (April) and second (July) shocks. Note the crosses.

(*Below*) Cracks at the back of the Brian Boru Hotel which reflect the stress concentration at the openings. (*Both photographs from the Warrnambool 'Standard'.*)

apparent quiescence during the last decade of improved instrumental coverage.

DAMAGE

Primary: There were apparently no large, important, engineered structures in the region of strong shaking but an interesting comment on the damage distribution was made in the *Argus* (16/7/1903): 'Stone buildings in the low-lying parts of the town and the Hopkins River have sustained the most damage'. This observation has two parts: firstly it is a comment on local construction techniques and secondly on the foundation materials.

Two residential buildings, one of two storeys, were sufficiently damaged to be condemned but none collapsed outright. Elsewhere, in churches, banks, hotels and public buildings, most damage involved fallen plaster from cornices, ceilings and walls, dislodged or fallen ornaments such as balustrades, or church crosses weighing up to 2½ cwt. (see Pl. 18, above) and collapsed chimneys. Many walls were cracked (see Pl. 18, below) and in the two buildings declared unsafe for habitation whole sections of the wall had fallen out.

In the cemetery, tombstones were shifted, many twisted, and some columns and headstones had fallen or sheared off at the base (see Plates 19, 20). The more severe damage in the July than in the April event may have been in part the result of cumulative effects of the two earthquakes. Cracks from the first earthquake were found to have been re-opened or widened by the second.

The church steeple at St. Josephs was twisted and sheared through seven metres from the top which, after the earthquake, was found to be offset some 2 cm east relative to the lower section. The steeple

PLATE 19

Tombstone shifted in the Warrnambool Cemetery. (*Photograph from the Warrnambool 'Standard'*.)

PLATE 20

Tombstone in the Warrnambool Cemetery rotated. Note displacement of top. (*Photograph from the Warrnambool 'Standard'*.)

top was subsequently shortened whilst being rebuilt. A large stone block was ejected from the steeple and its initial velocity, hence that of the steeple, must have been about 1 m/sec since it landed nearly four metres out from the wall where 'it made a hole about a foot deep in the earth'. This would accord with the comment of a passer-by that 'during the earth tremors the steeple swayed to and fro in a very alarming manner'. Several large (1000 gallon) full iron water tanks burst at their bases and a pedestrian suspension bridge over the Merri River was twisted and distorted.

The overall repair bill does not appear to have been costed but it was 'estimated at thousands of pounds' and a few individual estimates were made: St. John's Church £250, a similar amount for St. Joseph's Church, Victoria Hotel £80, the cemetery £600 — £800, a residence at Sherwood Park £800. To convert to 1977 $ values, these figures should be multiplied by about 24 which is twice the change in

the retail price index over that period.

Secondary: One perhaps surprising but noteworthy effect from an earthquake of this size was the widespread evidence of liquefaction in the intertidal zone at the mouth of the Hopkins and Merri Rivers. Liquefaction of a saturated soil occurs under cyclic loading when the pore-water pressure equals the confining pressure, at which point the effective stress on the soil structure is reduced to zero. Large deformation of overlying materials or structures may result depending on the confinement conditions.

Sand 'boils' or 'volcanoes' indicate that a flow path has opened to the surface venting the excess pore pressure. At Warrnambool, the ejected material, seemingly a black silty sand and water, came from a depth of at least two metres, the depth of the fissures, and formed craters up to two metres across and half a metre high. The subsidence of sand embankments along both rivers was no doubt associated with liquefaction of the underlying saturated sand layer.

Foundation failure may have been a prime cause of the severity of damage to low-lying buildings in the town. According to Gill (1943) one of the characteristics of the dune sandstone in the Warrnambool area is the presence of buried soil horizons which 'vary in thickness from 2 feet to a few inches'. A geomechanical investigation would soon indicate whether these dark, sandy soil horizons underlie, at shallow depth, the damaged areas. It is also likely that these low lying areas are either earlier courses of the Merri River or former swamps impounded by the aeolian dunes. Many of these swamps have since been reclaimed. During the April shake, the water appeared to boil, although 'sand boils' were not observed, presumably because they were underwater. Similar sand 'volcanoes' and boiling were observed close to the waterfront at Kingston, Robe and Beachport in South Australia, after the much bigger May 1897 earthquake there.

DISCUSSION

(1) Despite the relatively small size of this earthquake considerable damage was occasioned to rigid structures — the stone buildings and tombstones. This is explicable in terms of their lack of ductility coupled with the fact that their resonant frequency would lie in the peak range of the response spectrum for a *close* earthquake. Care should be taken in constructing non-ductile buildings in seismic zones, especially important rigid structures and particularly those with attachments of different natural frequency like nuclear containment vessels. Strict care should be observed even when large earthquakes are negligibly remote events.

(2) Given appropriate soil conditions, even a moderate earthquake (say magnitude above 5) can cause liquefaction, which could be disastrous for important structures whose foundations were not adequately designed for such effects. Designers of facilities sited close to the sea or to a lake or river, to make optimum use of port access or the convenient water supply, should be aware of the heightened environmental risk in a seismic zone. Local geology can compound the liquefaction problem in the case where a confined saturated silty sand overlies a relatively rigid basement, when energy will be trapped in the sand layer rather than radiated back into the bedrock. This can lead to a dramatic increase, relative to bedrock, in the duration of shaking, and either an increase or decrease in level depending on the time taken for the layer to fail.

(3) Both the above points depend on identification of active seismic zones. The discussion of the 1903 earthquakes and the brief résume of pre-1959 activity underscores the activity, minor though it is, of southwestern Victoria and forcefully illustrates the benefits of historical seismic studies.

ACKNOWLEDGMENTS

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STUDIES OF THE FAMILY PROTEACEAE II. FURTHER OBSERVATIONS ON THE ROOT MORPHOLOGY OF SOME AUSTRALIAN GENERA

By HELEN M. LEE (née PURNELL)*

ABSTRACT: Proteoid roots are recorded for *Bellendena montana*, *Cenarrhenes nitida* and *Franklandia fucifolia*. *Agastachys odorata* and *Symphionema montanum* do not develop proteoid roots. Some previously unreported features of the root systems are described.

INTRODUCTION

In an earlier paper the term 'proteoid root' was defined and the morphological and anatomical features of such roots described (Purnell 1960). A proteoid root was defined as the cluster of rootlets, of limited growth, which forms on a lateral root. The part of the lateral root which bears the rootlets is referred to as the axis of the proteoid root. If the axis is unbranched the proteoid root is said to be simple and if it is branched the proteoid root is said to be compound. The internal anatomy of the axis of a proteoid root resembles that of a normal lateral. The proteoid rootlets arise endogenously, have normal primary root structure, do not undergo secondary growth and bear long root hairs. Proteoid roots are seasonal structures and the rootlets are apparently functional for a limited period, sometimes as little as three months. The axis undergoes secondary growth, but the rootlets shrivel and slough off. The simple type of proteoid root is the most common and is typical of, for example, the genus *Hakea*.

Lamont (1974) and Pathmaranee (1974) have since reported the presence of proteoid roots on a variety of other genera and species within the family Proteaceae. In addition, proteoid roots have been described for *Viminaria juncea*, family Fabaceae (Lamont 1972a).

MATERIALS AND METHODS

The majority of the roots used in this study were collected in the field from small shrubs. Microtome sections were prepared from material fixed in formalin-acetic-alcohol and embedded in paraffin wax. Sections were stained with safranin and aniline blue.

ROOT MORPHOLOGY AND ANATOMY

(i) *Bellendena montana:* Venkata Rao (1971) reported the presence of proteoid roots on this species, but did not describe their morphology. The proteoid roots were simple, but the rootlets appeared to be less dense than those of *Hakea* spp., for example. Examination of serial sections of the proteoid roots showed that the rootlets each arose in the pericycle opposite a protoxylem pole, but in an irregular manner. That is, in any transverse section of a hexarch root there was only one rootlet, or occasionally two, three or four (Pl. 21 (1)). Thus, the rootlets were scattered along the axis of the proteoid root and this is the first record of a simple proteoid root in which the rootlets are not longitudinally contiguous. In other genera and species the simple proteoid roots resembled those of

TABLE 1.
SPECIES EXAMINED AND COLLECTION LOCALITIES

Species	Collection Locality
Agastachys odorata R.Br.	Near Hobart, Tasmania.
Bellendena montana R.Br.	Middlesex Plains and Mt. Rufus, Tasmania.
Cenarrhenes nitida Labill.	Near Cradle Mt. and Mt. King William I, Tasmania.
Franklandia fucifolia R.Br.	Nannup and Toompup, Western Australia.
Symphionema montanum R.Br.	Blue Mountains, New South Wales.

*Department of Botany, La Trobe University, Bundoora, Victoria 3083.

Hakea spp. in which rootlets emerged opposite every protoxylem pole in any transverse section and adjacent rootlets were longitudinally contiguous. (Purnell 1960, Lamont 1972b).

(ii) *Cenarrhenes nitida:* All the specimens examined bore simple proteoid roots. Examination of transverse sections through the axes of the proteoid roots showed a previously unrecorded type of development as the rootlets emerged in pairs opposite each protoxylem pole (Pl. 21 (2)), and vascular tissue from each member of the pair could be traced back to the same protoxylem pole. Therefore, all rows of rootlets along the axis of the proteoid root were double instead of the single rows as found on most proteoid roots. Lamont (1972b) reported the occurrence of some double rows of rootlets on proteoid roots collected from mature plants of *Hakea prostrata* R.Br. However, single rows also occurred on the same axis as the double rows and single rows of rootlets were typical of young plants of the same species. Young plants of *C. nitida* have not been examined.

(iii) *Franklandia fucifolia:* Lamont (1974) recorded compound proteoid roots for this species. In the compound proteoid root type described for *Banksia* spp. (Purnell 1960) and subsequently found to be typical of *Dryandra* spp., the axis was profusely branched and on each branch the rootlets emerged opposite each protoxylem pole in a transverse section and were longitudinally contiguous. The proteoid roots of *F. fucifolia* were found to be less complex than the *Banksia* type in that the axis was sparingly branched and the proteoid roots were distant from one another, that is, they did not emerge opposite each protoxylem pole and were not longitudinally contiguous. Part of the root system of a two-year old seedling is shown in Pl. 22 (3) and the scattered arrangement of the proteoid rootlets is evident. The axis of each proteoid root is diarch, but the rootlets are monarch and of limited growth. The rootlets all give rise to a dense growth of root hairs.

(iv) *Agastachys odorata* and *Symphionema montanum:* Pathmaranee (1974) reported the absence of proteoid roots in *Symphionema montanum* and described zones of dense root hair development in which the root hairs were longer than those found in other parts of the root system.

Observations made during the current study confirmed Pathmaranee's findings and it was found that *Agastachys odorata* also did not form proteoid roots. In both species long root hairs developed on sections of the lateral roots and these clusters of root hairs bore a superficial resemblance to proteoid roots, the effect being enhanced by the humus and sand particles entangled in the root hairs (Pl. 21 (4), (7); Pl. 22 (6)).

Some unusual features were noted on examination of tranverse sections cut through the root hair zones of the lateral roots of each species. In *S. montanum* the epidermal cells were long and narrow, that is, the length of the tangential walls was small compared with the radial walls (Pl. 21 (5)). Nearly all the epidermal cells appeared to be piliferous and so the root hair growth was very dense indeed. In *A. odorata* the root hairs were not as numerous as those of *S. montanum* and examination of serial transverse sections of the roots showed that only a small proportion of the epidermal cells gave rise to a root hair. Pl. 21 (8) shows a transverse section of a small lateral root in which only two of the twelve epidermal cells have produced a root hair.

DISCUSSION

Since proteoid roots were first described (Purnell 1960) they have been observed in many other genera and species within the Proteaceae by various workers, including Lamont (1974) and Pathmaranee (1974). However, it is of interest that there are several genera in which proteoid roots do not occur. These include *Persoonia*, *Acidonia* (formerly *Persoonia* sect. Acranthera Benth.), *Pycnonia* (formerly *Persoonia* sect. Pycnostylis Meissn.), *Symphionema* and *Agastachys*. In addition, preliminary work suggests that *Placospermum coriaceum* White and Francis does not form proteoid roots (Lee, unpublished data).

Johnson and Briggs (1975) have now recognised five subfamilies in a revised classification of the Proteaceae and have proposed schemes of phylogenetic relationships within each subfamily. Table 2 summarises the information about occurrence of proteoid roots within each subfamily.

TABLE 2.
SUMMARY OF CURRENT INFORMATION ON THE OCCURRENCE OF PROTEOID ROOTS IN THE SUBFAMILIES OF PROTEACEAE

Subfamily	*No. genera in sub-family*	*No. genera examined*	*Genera with proteoid roots*	*Genera no proteoid roots*
Grevilleoideae	40	20	20	—
Proteoideae	26	16	14	2
Persoonioideae	7	5	1	4
Sphalmioideae	1	1	1	—
Carnarvonioideae	1	—	—	—

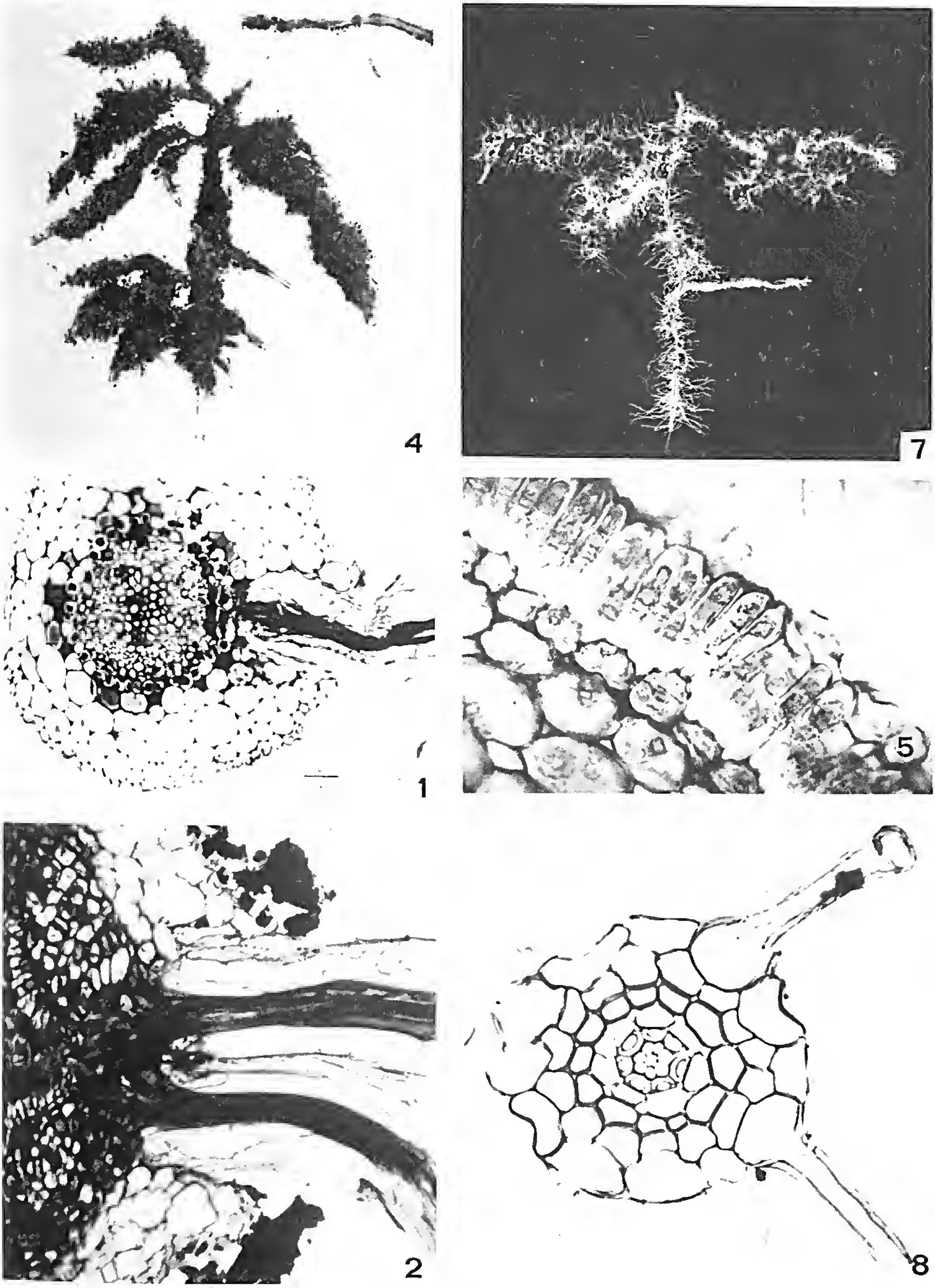

PLATE 21

(1) *Bellendena montana* T.S. axis of a proteoid root, X 120. (2) *Cenarrhenes nitida* T.S. part of proteoid root axis, X 80. (4) *Symphionema montanum* part of the root system of a small plant, X 1. (5) *Symphionema montanum* T.S. young lateral root, X 500. (7) *Agastachys odorata* part of the root system of a small plant, X 1. (8) *Agastachys odorata* T.S. small lateral root, X 250.

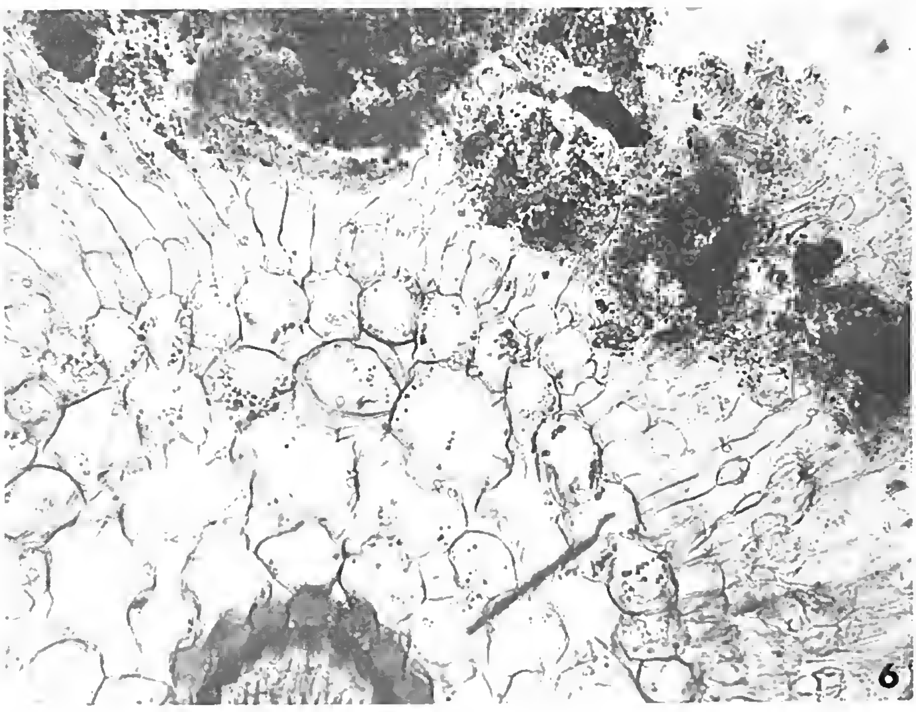

PLATE 22
(3) *Franklandia fucifolia* part of the root system of a young plant grown from seed, X 2.
(6) *Symphionema montanum* T.S. through the root hair zone of a lateral root, X 250.

Of the taxa so far studied, those which do not form proteoid roots are members of the subfamilies Persoonioideae and Proteoideae. In their comments on the features of these subfamilies Johnson and Briggs have pointed out that the greatest number of primitive character-states seems to be found within the Persoonioideae. Further, the genera *Agastachys* and *Symphionema* are included in the subtribe Cenarrheninae, tribe Conospermeae of the Proteoideae, in which other relict genera with many primitive characteristics have been placed.

There is no evidence to suggest that presence or absence of proteoid roots is related to the ecology of the species concerned since the distribution of genera and species having each type of root ranges over a variety of habitats. In view of this and because of the arguments on phylogeny already presented it is postulated that the formation of proteoid roots is an advanced character within the family. Furthermore, the two genera *Banksia* and *Dryandra* in which the complex compound proteoid root type is found are considered by Johnson and Briggs to possess many advanced characters, so it is reasonable to assume that the compound proteoid root is a more advanced state than the simple type.

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25

SHELLY BEACHES ON THE VICTORIAN COAST

By ROBERT A. GELL*

ABSTRACT: The accumulation of biogenic sediment on the Victorian coast to form shelly beaches depends upon the availability of shelly debris and therefore on the ecology and local population densities of contributing species (Table 1). Shallow marine embayments and estuaries, shore platforms and offshore reefs are areas where shelly beaches are often found.

Shelly beaches exist either as a veneer over sandy material or as a thick deposit consisting solely of shells and shell debris. As the shells are usually fragmented and worn, species identification is difficult. Shelly beaches are deposited by constructive wave energy, and are often concentrated locally by wave refraction, or by storm waves at higher water levels; they are often associated with accumulation forms such as spits, tombolos, cheniers and swash bars.

INTRODUCTION

Shelly beaches are infrequent on the coast of Victoria (Fig. 1). Littoral sediments are composed of quartz with a variable concentration of sand-sized biogenic material which may account for more than 50 percent of the sediment on beaches west of Wilsons Promontory. Shepard (1973, p.132) states that shelly beaches are rare in high latitudes, except where terrigenous material is scarce; in general temperate beaches are of quartz. Raymond and Stetson (1932) attributed the development of a shelly beach on the coast of Maine to a lack of terrigenous mineral sand; and similarly on the Melbourne coast, beaches are becoming progressively more calcareous after construction of sea walls has reduced cliff erosion and diminished the terrigenous sand supply to the beaches (Bird 1970). Leontiev and Khalilov (1976) report that the carbonate content in sediments of the eastern shore of the Caspian Sea is 80 to 90 percent, and that shelly material on the western coast varies from 10 to 50 percent and sometimes reaches 80 to 90 percent. Mamykina and Khrustalev (1976) report that in the Sea of Azov, four million tons of shelly material were delivered to the shoreline annually: shell productivity is related to the volume of dissolved calcium carbonate entering from the Don and Kuban rivers. As a result, beach bars at river mouths composed of sands had 70 to 80 percent shell content. Other descriptions of shelly beaches in extra-tropical areas include Zenkovich (1976, p.115), Watson (1971) and Keary (1968) who correlates biogenic carbonate content with degree of exposure to prevailing winds and consequently to waves.

MORPHOLOGY AND FORMATION

The components of beach deposits on the Victorian coast depend upon the availability of various kinds of source material. Beach material may be derived from eroding coastlines, from rivers that deposit sediment at the coast, from alongshore by lateral beach drifting, or from the sea floor, swept landward by wave action. At a number of localities along the Victorian coast, calcareous remains of marine organisms, both modern and fossil have accumulated to form shelly beaches (Pl. 23, (1), (2)). Description of a beach as 'shelly' has been a subjective classification because of variations in beach morphology and composition, but in this paper the term refers to beaches visibly dominated by broken or entire shell material greater than sand-size diameter. Zenkovich (1967, p.76) uses the term shell debris to describe organic elements such as shells and shell fragments and the remains of other organisms in beach material, and shell gravel to describe material which is broken, graded and sometimes rounded. Some shelly beaches are only a veneer of shells on a quartzose or calcareous sandy beach; others are composed almost entirely of shells and shelly debris, as in Bridgewater Bay (Pl. 24 (3), (4)), and along the muddy shorelines on the northern side of Westernport Bay.

Because of the high permeability of coarse

*Department of Geography, Melbourne State College, 757 Swanston Street, Carlton, Victoria 3053.

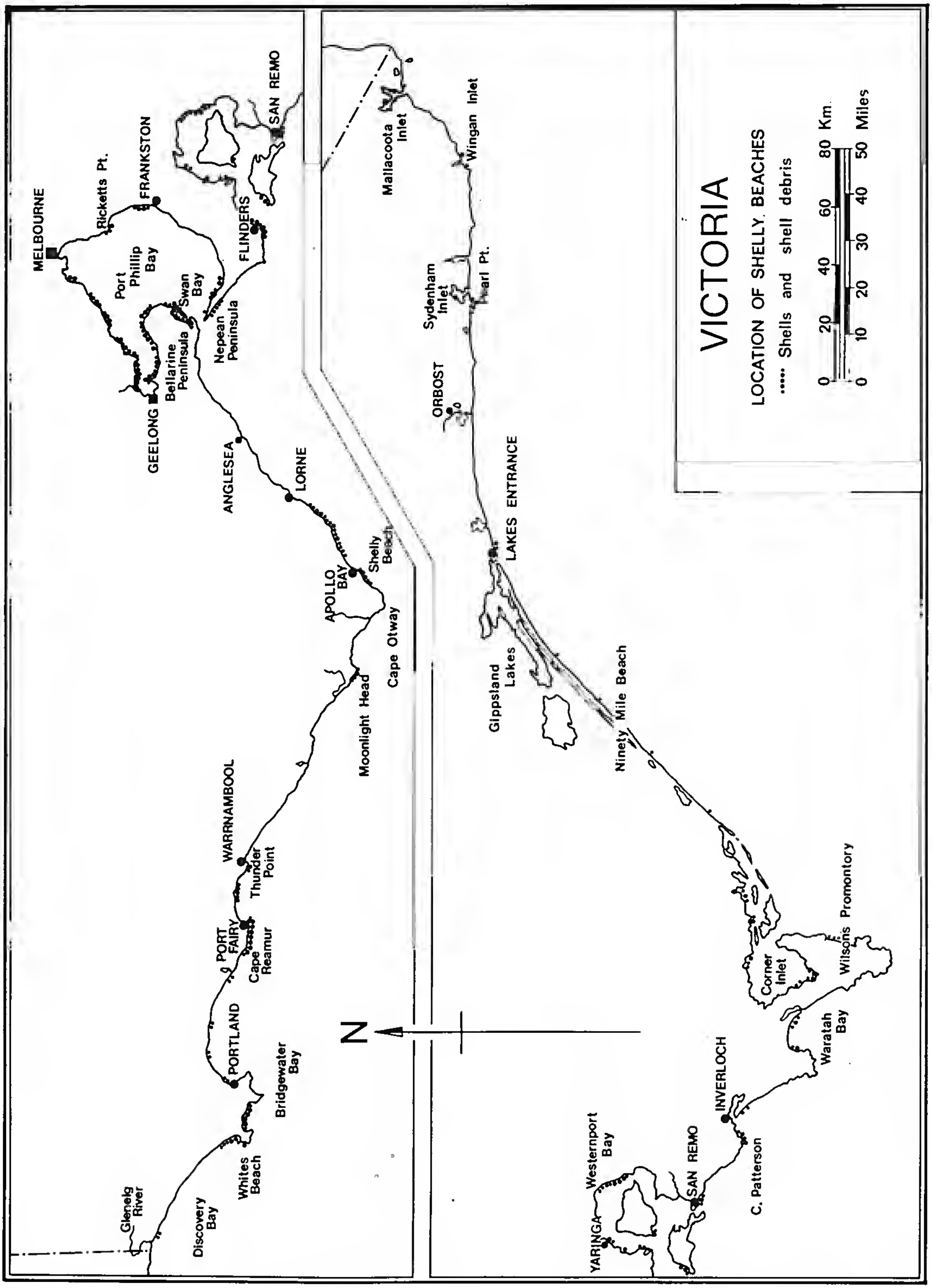

FIG. 1 — Location of Shelly Beaches on the Victorian Coast.

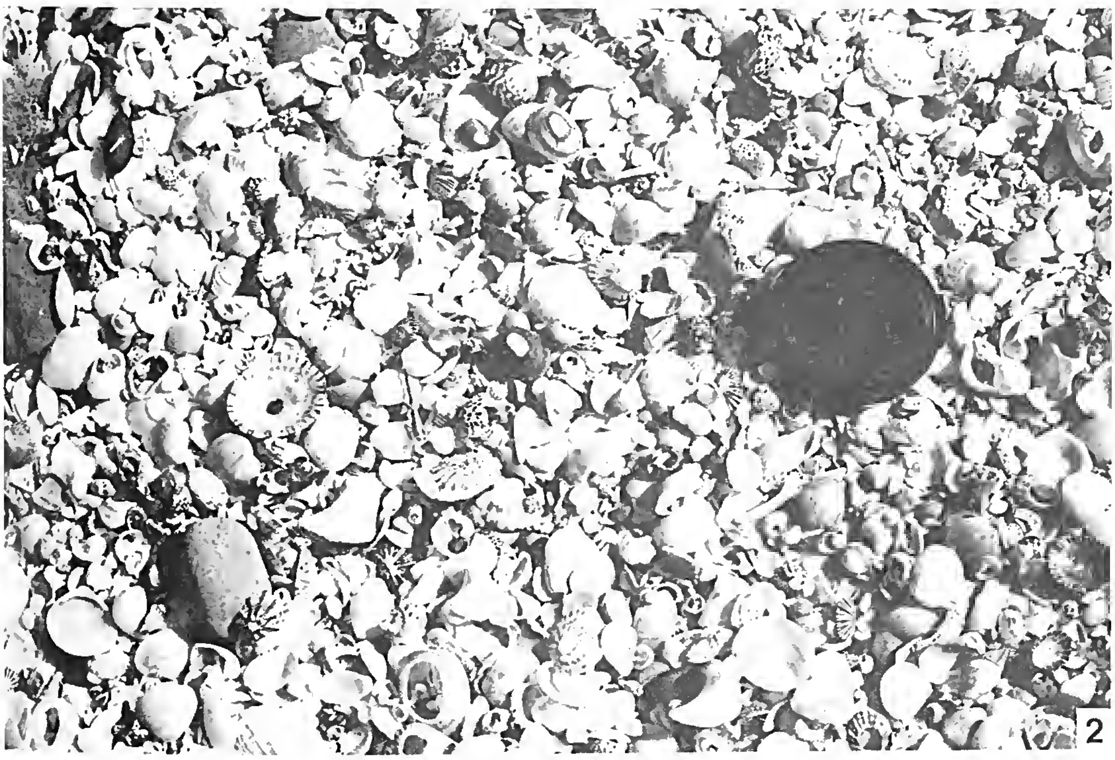

PLATE 23

(1) 'Shelly Beach' near Elliott River, Otway Coast, showing deep shell drifts behind arkosic shore platform.

(2) Shell debris and pebble accumulation at 'Shelly Beach' near Elliott River, Otway Coast.

3

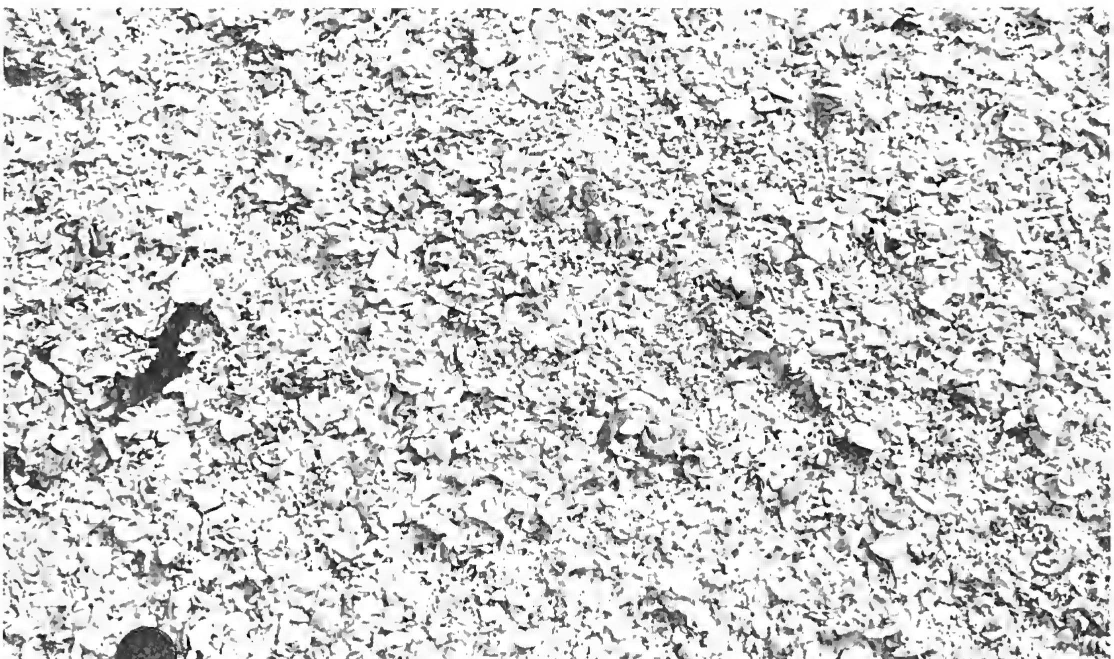

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PLATE 24
(3) 'Shelly Beach', Bridgewater Bay near Portland.
(4) Shells and shell debris at 'Shelly Beach', Bridgewater Bay.

material, shelly beaches are more affected by wave swash than by backwash. Shells are moved up the beach by the swash but the backwash is rarely strong enough to move them back down the beach face, and so they accumulate. Backwash is effective in sorting shelly sediment so that the largest shells remain on the surface overlying the smaller fragments. Shelly beaches are also sorted across the beach as waves move the large particles up the shore to accumulate on the upper beach, and the smaller particles are displaced down the slope by the backwash. This further enhances the concavity of the beach profile. Aeolian deflation is effective in sorting shell material from sand on Padre Island, Texas (Watson 1971), and is evidence that large carbonate accumulations can occur in areas of great terrigenous sediment supply; in most cases a large terrigenous sediment supply causes reduced carbonate content. Rusnak *et al.* (1966), working on the Florida coast showed that low concentrations of shell material near Jacksonville were attributable to erosion of carbonate-poor 'older' dune sands whilst beaches of south Florida which receive little quartz sand from northern flood plains have higher values.

Shelly beaches are found only where there has been a sustained supply of shells on the shoreline. The available habitat for marine molluscs at different localities along the shoreline and offshore regulates the population density of contributing species available for incorporation in beaches (Table 1). Extensive molluscan populations supply nearby beaches with a large volume of shells. In the southern United States the carbonate content of beach and dune sediments is controlled by the availability of materials and also by wave energy, with the carbonate fraction small on the low wave energy coast of Georgia, increasing to the north where energy is higher, and greatly to the south where large amounts of biogenic carbonate material are available (Giles & Pilkey 1965).

Where shelly material is exposed to high wave energy disintegration and comminution to calcareous sand occur (Davies 1972, p.113). This is the case at Whites Beach near Cape Duquesne where the beach consists entirely of shell fragments of coarse sand size, 1.0 — 2.0 mm. Shells at Thunder Beach, Warrnambool, are fragmented and worn; the fragile shells have been reduced to sand-sized particles, and only the stronger segments of gastropods, such as the columellas and operculums of *Subninella undulata* (Solander 1786) remain as large recognisable fragments of molluscs. These fragments are mixed with sand and sandstone pebbles by waves breaking on the beach. By contrast the low wave energy shores of Westernport Bay have shelly beaches on which delicate shells such as *Pholas australasiae* (Sowerby 1849) remain intact. They have been swept onshore by waves to accumulate as a veneer of whole shells, either on the wave-cut clay platforms or over the existing beach material of coarse quartz sand, so that the shelly zone remains a separate entity.

Shelly beaches are frequently found on cuspate spits and tombolos, where reduction of wave energy by refraction enhances sediment accumulation. For example, on the Otway coast where rocky shorelines provide suitable habitats for a wide variety of molluscs, small cuspate spits and tombolos are often found in the lee of offshore reefs, consisting of shells or shelly veneers on sand or gravel. Wave refraction in Kitty Miller Bay on the south coast of Phillip Island reduces wave height at each end of the beach, and the resulting waves cause the accumulation of shelly material from nearby rocky shores along the limit of swash at high tide. Bridgewater Bay near Portland in western Victoria is a shallow sandy bay which contains numerous offshore reefs with associated algal growth. These provide a habitat for a large number of pelecypods and some gastropods. Constructive wave action moves shells on to the shoreline, and extensive shelly deposits have formed. These are frequently associated with calcarenite headlands like those which occur at 'Shelly Beach', where wave refraction around reefs causes the construction of deep shell drifts in sectors adjacent to shoreline, and headland features where wave height is reduced (Pl. 24 (3)).

There are a variety of structural traps in the coastal zone which retain sediment, particularly shells. Irregularities within a shore platform may be sites of accumulation of shelly debris. The arkosic shore platforms of the Otway coast have a rectangular jointing pattern, with joints often marked out as ridges as a result of ferruginization along the joint planes. These ridges form an effective shell trap. Shore platforms in the aeolian calcarenite of the Nepean Peninsula have surface features such as lapiés and potholes which trap shells migrating across the platform, and large rock pools provide a sink for all debris including shells. At Pearl Point, near Sydenham Inlet, the shore platform is cut in steeply dipping Ordovician sandstones which strike north/south, and differential erosion has produced a series of parallel strike ridges with channels almost at right angles to the wave crests. Shells and pebbles are trapped within these channels, and large gastropods accumulate to depths of 20 cm. On similar high

wave energy coasts shells may be moved on to the backshore in large volumes where a cleft in the shore platform constricts waves and produces strong currents which can lift material from the sea floor onto the beach behind.

Beaches at Cape Reamur and Killarney near Port Fairy are built behind extensive and intricate shore platforms and offshore reefs of Newer Basalt. The platform and reefs absorb wave energy and provide suitable habitats for a variety of small gastropods. The columnar morphology of the basalt platforms intercepts shells in basins between the joint planes, and these shells are later distributed on to the beaches behind. Columnar jointing of basalt in shore platforms at Cat Bay on Phillip Island traps shells in the same manner. Artificial structures such as groynes and jetties influence wave refraction and the longshore drifting of sediment, and can also act as shell traps.

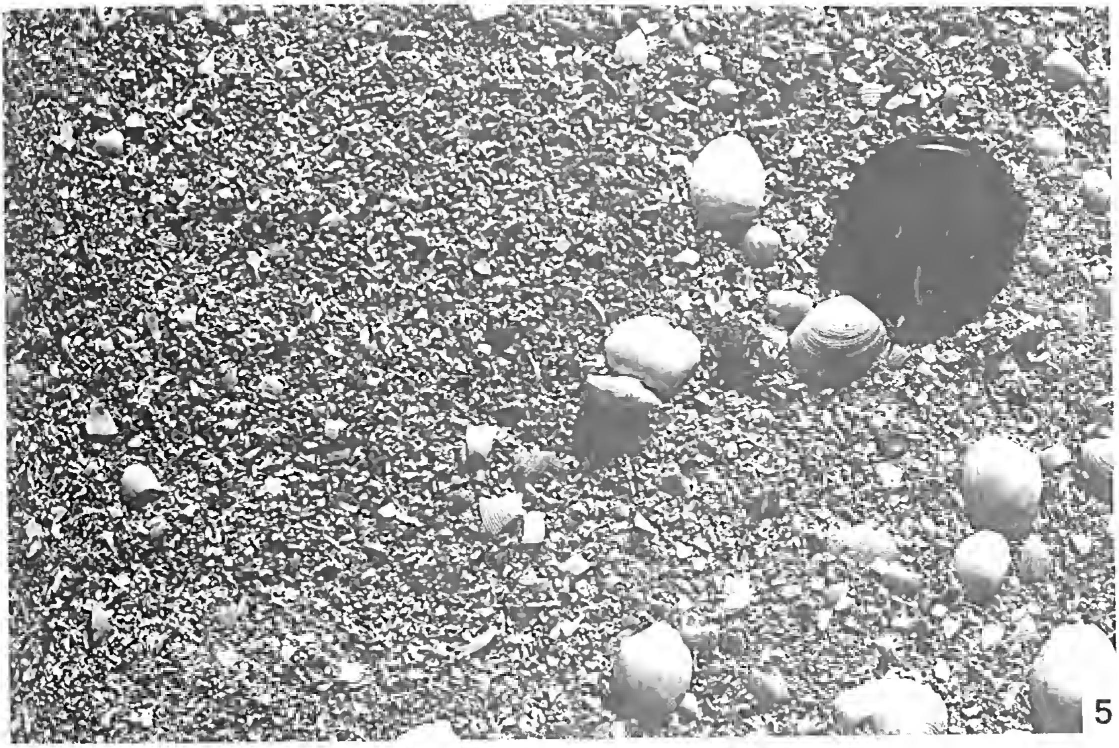
The low wave energy coasts of Port Phillip and Westernport Bays have numerous shelly sectors. Swan Bay and Corio Bay are sheltered areas with shallow, muddy floors which support large populations of molluscs. Most of the beach deposits on the northern shore of Corio Bay consist entirely of small shells (Pl. 25 (5)); at Avalon the shells are mixed with a fine white quartz sand, and along the whole northwest coast of Port Phillip Bay shelly strand lines of large shells may accumulate after storms to heights up to 25 cm above the former beach surface. Other accumulation forms in the area, such as the paired spits at the mouth of Limeburners Bay, 'The Island' and 'The Sand Hummocks' (Pl. 26 (7)), and the Point Henry spit, are composed almost entirely of shells, and the shallow depositional shores of Mud Islands have extensive accumulations of shelly debris. The northern part of Westernport Bay is another low wave energy mudflat habitat. Parts of the shore here are scalloped in plan, and longshore drift has concentrated shells and coarse sand from local rivers in pockets along the coast. The shells are easily transported shoreward from the bay floor to form a veneer on the muddy shoreline at the limit of wave swash. Frequently two parallel strand lines are found on one beach, the result of reworking by waves at higher high tide and lower high tide during a twenty-four hour period (Gell 1974), (Pl. 25(6)). In the Sea of Azov, Zenkovich (1967, p.115) observed shoreward movement of shells from the muddy bottom after the bottom material had been stirred up, and the author has observed that accumulation rates are accelerated at periods of higher wave energy during storms. Shelly strand lines up to 15 cm in height may be built at the rear of a bay and shells swept into the salt marsh during storms at high spring tide form cheniers (Pl. 26(8)). Van Straaten (1952) explains that shell beds intercalated between marsh deposits in the Dutch Wadden Sea formed in this way during gales, when the water level rises well above mean high tide and mollusc valves are washed on to the marsh surface. These shell beds are typical elements of sea built levees in the area and lens out over a few metres when traced landward.

The importance of estuaries and other shallow marine areas as a sheltered habitat for molluscs is evident on the East Gippsland coast. There are few local concentrations of shells on the ocean beaches apart from beaches adjacent to large estuaries. Mallacoota, Wingan and Sydenham Inlets provide a more sheltered muddy habitat for the shells which have accumulated along the shores of these estuaries and a local source for shell accumulations on ocean beaches. On the Florida coast widely divergent values of average shell content are attributable to carbonate-rich inlet areas which have a high standing crop of shell forms and contribute a higher percentage of shell than a normal beach (Rusnak *et al.* 1966).

Accumulations of shelly material at the shoreline need not necessarily be derived from recently living molluscs. Fossil marine shell beds of the kind exposed in Swan Bay are locally a plentiful source of shelly beach material similar in origin to calcareous beaches in Scotland (Raymond & Hutchins 1932). Much of the shell material behind the basalt boulders at Cape Reamur may be material reworked from emerged shell grit terraces (Gill 1973). Aboriginal kitchen middens, common on the Victorian coast, are another source of shells, delivered to the shoreline where dune middens have been exposed by wave attack. Gill (1951) has established criteria for distinguishing between marine shell beds and coastal kitchen middens *in situ*, but the distinction may be less obvious once the shell material is incorporated into a shelly beach: the reworking of southern New South Wales coastal midden deposits by storm waves has been described by Hughes and Sullivan (1974). Some of the shells delivered to the northern shoreline of Westernport Bay appear to have been eroded out by currents from a marine shellbed which extends beneath the inter-tidal and sub-tidal mud-flats, and is locally exposed in meandering tidal channels (Miles 1976).

DISTRIBUTION AND SPECIES CONTENT

The distribution and relative abundance of extant molluscs found in Victorian shelly beaches is



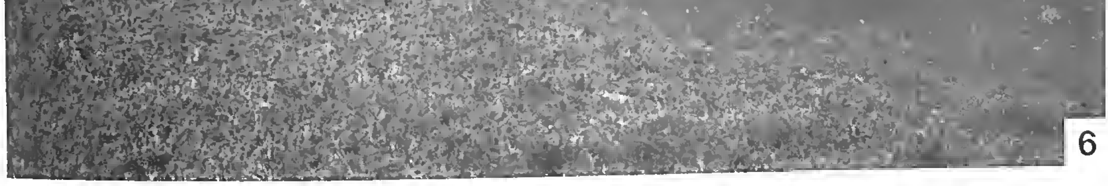


PLATE 25

(5) Accumulation of small shells at 'The Island' on the northwestern shore of Port Phillip Bay.

(6) Strandlines at the higher tide mark and lower high tide mark, northeastern Westernport Bay. Shelly cheniers are evident on the salt marsh surface behind bays.

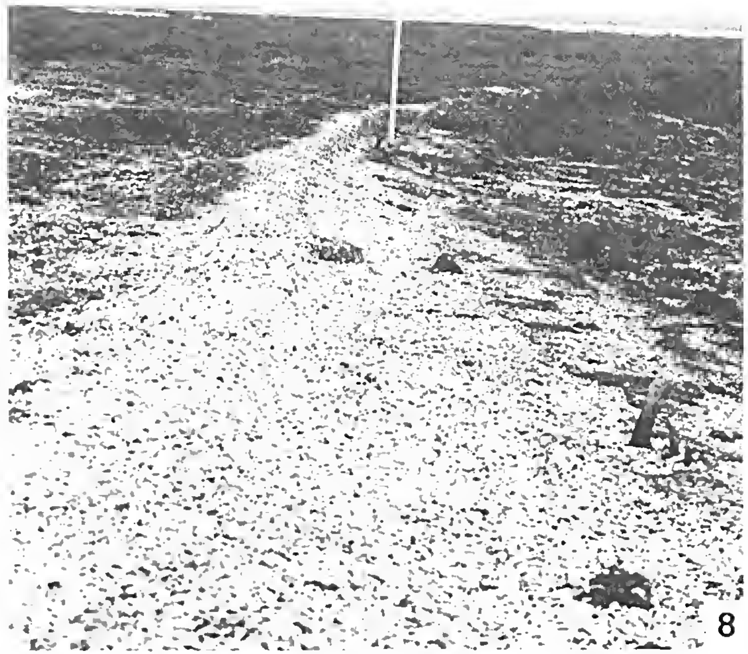


PLATE 26
(7) Shelly shore of 'The Island' on the northwestern shore of Port Phillip Bay.
(8) Shell strand on northeastern Westernport Bay shore.

TABLE 1

DISTRIBUTION AND RELATIVE ABUNDANCE OF SHELL SPECIES IN SHELLY BEACHES ON THE VICTORIAN COAST.

Amphineura ← Gastropoda →

SAMPLE LOCATIONS	Poneroplax sp.	Ischnochiton sp.	Haliotis ruber *	Haliotis emmae *	Haliotis roei *	Haliotis laevigata *	Scutus antipodes	Notomella candida	Montfortula rugosa	Hemitoma subemarginata	Amblychilepas javanicensis	Amblychilepas nigrita	Macroschisma tasmaniae	Macroschisma producta	Elegidion audax	Patellanax peroni	Patellanax chapmani	Cellana tramoserica	Patelloida alticostata	Patelloida victoriana	Notoacmea sp.
Family	MOPALIIDAE	ISCHNOCHITONIDAE	HALIOTIDAE				FISSURELLIDAE									PATELLIDAE			ACMAEIDAE		
HABITAT	Ri	Ri	Rs	Rs	Rs	Rs	Rs	Rs	Ri	Rs	Ri	Ri	Ri	Ri	Ri	Ri	Ri	Ri	Ri	Ri	Ri
DISCOVERY BAY																				•	
WHITES BEACH							•											●	•		
BRIDGEWATER BAY	•										●										
SHELLY BEACH (BRIDGEWATER)	•										●									•	•
PORTLAND BAY			●	•	•													•			•
CAPE REAMUR - PORT FAIRY		•	●					•	•							•		●			•
THUNDER BEACH		•	●															•		•	•
MOONLIGHT HEAD															•	•		●	•	●	
SHELLY BEACH (OTWAYS)		•									•	•		•			•	•	•	●	
APOLLO BAY - SKENES CK.	•	•	•				•											•	•	•	
KENNETT RIV - LORNE	•	•	•				•											●		•	
SWAN BAY & ENVIRONS																					
BELLARINE PENINSULA																					
NORTHWEST PORT PHILLIP BAY																					
RICKETTS POINT - BEAUMARIS			●															•			
FRANKSTON - LONG ISLAND																					
DROMANA - McCRAE																					
TYRONE FORESHORE																		•			
COLLINS BAY			●	•		•								•							
MUD ISLANDS																					
NEPEAN OCEAN COAST	•		●	•		•	•				•			•				●	•		
FLINDERS	•		●															●			
SHOREHAM																		•			
STONY POINT - YARINGA																					
NORTHEAST WESTERNPORT																					
WESTERN PHILLIP ISLAND			•							•			•					●	•		
SHELLY BEACH (SAN REMO)	•	•	•															●	•		
CAPE PATTERSON			•															•		•	
INVERLOCH		•																•			
WARATAH BAY																					
WILSON'S PROMONTORY																		•			
CORNER INLET																					
NINETY MILE BEACH			•															•	•		
LAKES ENTRANCE																					
PEARL POINT																					
MINGAN INLET & ENVIRONS			•															•			•
MALLACOOTA INLET & ENVIRONS																					

SAMPLE LOCATIONS	Herpetoma aspersa	Stomatella imbricata	Calliostoma spp.	Cantharidus spp.	Phasianotrochus sp.	Bankivia fasciata	Austrocochlea spp.	Clanculus spp.	Subninella undulata	Phasianella australis	Phasianella ventricosa	Phasianella variegata	Nerita atramentosa +	Littorina unifasciata +	Littorina praetermissa +	Bembicium nanum	Bembicium auratum	Ctenocolpus australis	Gazameda gunni	Pyrazus ebininus	Velacumantus australis	Zeacumantus diemenensis	Diala monile	Granuliscala granosa	Opalia australis	Stilifer sp.
Family	TROCHIDAE								TURBINIDAE				NERITIDAE	LITTORINIDAE				TURRITELLIDAE		POTAMIDIDAE			CERITHIIDAE	SCALIDAE		STILIFERIDAE
HABITAT	Rs	Rs	Rs	Rs	Rs	Rs	Ri	Rs	Rs	Rs	Rs	Rs	Ri	Ri	Ri	Ri	Ri	Rs	Ss	Si	Si	Si	Si	Ri	Ri	Ss
DISCOVERY BAY																										
WHITES BEACH																										
BRIDGEWATER BAY						●																				
SHELLY BEACH (BRIDGEWATER)						●	•																			
PORTLAND BAY					•				●	●	•	•														
CAPE REAMUR - PORT FAIRY	•			•	•		•	•	●			•	●	•	•	•						•		•	●	
THUNDER BEACH							•		●																	
MOONLIGHT HEAD							•		●																	
SHELLY BEACH (OTWAYS)				•			•		●		•					•									•	
APOLLO BAY - SKENES CK.			•				●		●		•														•	
KENNETT RIV - LORNE				•	•		●		●																	
SWAN BAY & ENVIRONS																						●				
BELLARINE PENINSULA																					●	●	●			
NORTHWEST PORT PHILLIP BAY							•														●	●	•			
RICKETTS POINT - BEAUMARIS							•		●																	
FRANKSTON - LONG ISLAND																										
DROMANA - McCRAE																										
TYRONE FORESHORE																										
COLLINS BAY				•	•		●		●	●	•	•														
MUD ISLANDS										•	•											•				
NEPEAN OCEAN COAST				•	•		●		●					•			•									
FLINDERS			•	●	•	•	●			•	•	•	•				●									
SHOREHAM							●										●									
STONY POINT - YARINGA																										
NORTHEAST WESTERNPORT			•	•			•	•														●				•
WESTERN PHILLIP ISLAND	•	•		•			●	•			•		•				•					•				
SHELLY BEACH (SAN REMO)				•	•		●		•		•	•	•												•	
CAPE PATTERSON			•	•			●	•	•				●									•				
INVERLOCH																										
WARATAH BAY																			•							
WILSON'S PROMONTORY																			•							
CORNER INLET																		•				•				
NINETY MILE BEACH						●													•							
LAKES ENTRANCE																			●	•						
PEARL POINT																										
MINGAN INLET & ENVIRONS						•	•												•	●						
MALLACOOTA INLET & ENVIRONS							•		•								•		•	●		●				

NB. Taxonomy follows that of Macpherson and Gabriel (1962) except where indicated * Shepard, S.A. 1973
+ Underwood, A.J. (1974).

KEY TO SCALE OF RELATIVE ABUNDANCE

Rare	1%	•
Occasional	1-10%	•
Frequent	10-45%	●
Very frequent	45%	●

KEY TO HABITAT TYPE OF EXTANT SPECIES

Rocky substrate:	intertidal	Ri
	subtidal	Rs
Soft substrate:	intertidal	Si
	subtidal	Ss
Free swimming:		F

TABLE 1 (Continued)

DISTRIBUTION AND RELATIVE ABUNDANCE OF SHELL

Gastropoda

SAMPLE LOCATIONS	Sigapatella calyptraeformis	Polinices conicus	Polinices sordidus	Mammilla melastoma	Sigaretotrema umbilicata	Notocypraea spp.	Ellatrivia merces	Antephalium semigranosum	Xenogalea spectabilis	Xenogalea nivea
	CALYPTRAEIDAE	NATICIDAE				CYPRAEIDAE		CASSIDIDAE		
HABITAT	Rs	Si	Si	Si	Si	Rs	Rs	Ss	Ss	Ss
DISCOVERY BAY										•
WHITES BEACH										
BRIDGEWATER BAY										
SHELLY BEACH (BRIDGEWATER)		●								
PORTLAND BAY										
CAPE REAMUR - PORT FAIRY						●				
THUNDER BEACH										
MOONLIGHT HEAD										
SHELLY BEACH (OTWAYS)		•				●				
APOLLO BAY - SKENES CK.	●						●			
KENNETT RIV - LORNE	•									
SWAN BAY & ENVIRONS			⬤							
BELLARINE PENINSULA		●			•					
NORTHWEST PORT PHILLIP BAY			●							
RICKETTS POINT - BEAUMARIS										
FRANKSTON - LONG ISLAND										
OROMANA - McCRAE										
TYRONE FORESHORE										
COLLINS BAY			●			●	•			
MUD ISLANDS						●		●		
NEPEAN OCEAN COAST						•	•			
FLINDERS	•					•	•			
SHOREHAM						•				
STONY POINT - YARINGA										
NORTHEAST WESTERNPORT			●							
WESTERN PHILLIP ISLAND						•	•			
SHELLY BEACH (SAN REMO)		•				•				
CAPE PATTERSON						•				
INVERLOCH										
WARATAH BAY										
WILSON'S PROMONTORY										
CORNER INLET			⬤							
NINETY MILE BEACH									•	
LAKES ENTRANCE										
PEARL POINT						•				
WINGAN INLET & ENVIRONS				⬤					•	
MALLACOOTA INLET & ENVIRONS		⬤				●			•	

SAMPLE LOCATIONS	Cymatiella spp.	Mayena australasia	Cabestana spengleri	Monoplex australasiae	Charonia rubicunda	Pterynotus triformis	Bedeva paivae	Maculotriton australis	Lepsiella reticulata	Lepsiella vinosa	Agnewia tritoniformis	Dicathais spp.
	CYMATIIDAE					MURICIDAE			THAIDAE			
HABITAT	Ss	Ri	Rs	Rs	Ri	Rs	Rs	Rs	Ri	Ri	Rs	Ri
DISCOVERY BAY												●
WHITES BEACH												⬤
BRIDGEWATER BAY												●
SHELLY BEACH (BRIDGEWATER)												
PORTLAND BAY			●									
CAPE REAMUR - PORT FAIRY	●							•	•	•		●
THUNDER BEACH	•											●
MOONLIGHT HEAD												●
SHELLY BEACH (OTWAYS)	●		●						•		•	⬤
APOLLO BAY - SKENES CK.	●		●							●		●
KENNETT RIV - LORNE	●		●							●		●
SWAN BAY & ENVIRONS							•		●		•	
BELLARINE PENINSULA							●				●	
NORTHWEST PORT PHILLIP BAY						•	●					
RICKETTS POINT - BEAUMARIS												
FRANKSTON - LONG ISLAND												
OROMANA - McCRAE												
TYRONE FORESHORE												
COLLINS BAY	•		●			•						•
MUD ISLANDS			●				●					
NEPEAN OCEAN COAST	•		●									●
FLINDERS	●								•	•		
SHOREHAM	●						●					
STONY POINT - YARINGA												
NORTHEAST WESTERNPORT									●			
WESTERN PHILLIP ISLAND	●		●						●			
SHELLY BEACH (SAN REMO)	●											●
CAPE PATTERSON	•									•		●
INVERLOCH												
WARATAH BAY												
WILSON'S PROMONTORY												
CORNER INLET												
NINETY MILE BEACH		●	●									
LAKES ENTRANCE			●									
PEARL POINT		●	⬤	●	●				•	•		●
WINGAN INLET & ENVIRONS												•
MALLACOOTA INLET & ENVIRONS							●					●

SAMPLE LOCATIONS	Dentimitrella semiconvexa	Dentimitrella pulla	Austrosipho grandis	Austrosipho waitei	Cominella eburnea	Cominella lineolata	Tasmeuthria clarkei	Parcanassa pauperata	Parcanassa burchardi	Niotha pyrrhus	Dolicholatirus spiceri	Pleuroploca australasia	Fusus novae-hollandiae	Fusus australis
	COLUMBELLIDAE		BUCCINIDAE					NASSIDAE			FASCIOLARIIDAE			
HABITAT	Ss	Rs	Ss	Ss	Si	Rs	Rs	Si	Si	Si	Ss	Ss	Ss	Ss
DISCOVERY BAY														
WHITES BEACH														
BRIDGEWATER BAY														
SHELLY BEACH (BRIDGEWATER)						●								
PORTLAND BAY														
CAPE REAMUR - PORT FAIRY	•					⬤								
THUNDER BEACH						●								
MOONLIGHT HEAD														
SHELLY BEACH (OTWAYS)						⬤								
APOLLO BAY - SKENES CK.						⬤								
KENNETT RIV - LORNE						⬤								
SWAN BAY & ENVIRONS							●					●		
BELLARINE PENINSULA			•			●								
NORTHWEST PORT PHILLIP BAY			•		●									
RICKETTS POINT - BEAUMARIS						●								
FRANKSTON - LONG ISLAND														
OROMANA - McCRAE														
TYRONE FORESHORE														
COLLINS BAY						•		•		•		●		
MUD ISLANDS			●									●		
NEPEAN OCEAN COAST						●				●				
FLINDERS						●		●		●				
SHOREHAM						●								
STONY POINT - YARINGA														
NORTHEAST WESTERNPORT	•				●				•	•				
WESTERN PHILLIP ISLAND	●	•			●	⬤								
SHELLY BEACH (SAN REMO)	●				●	⬤								
CAPE PATTERSON	●					●					•			
INVERLOCH														
WARATAH BAY														
WILSON'S PROMONTORY														
CORNER INLET													•	
NINETY MILE BEACH													•	●
LAKES ENTRANCE					•	●			●					•
PEARL POINT				●									●	
WINGAN INLET & ENVIRONS													•	●
MALLACOOTA INLET & ENVIRONS						⬤							●	

SAMPLE LOCATIONS	Austromitra tasmanica	Eumitra australis	Eumitra badia	Eumitra glabra	Lyria mitraeformis	Mamillana mamilla	Amorena undulata	Sydaphera lactea	Sydaphera undulata	Nevia spirata	Epidirona quoyi	Floraconus anemone	Parviconus rutilus
	MITRIDAE				VOLUTIDAE			CANCELLARIIDAE			TURRIDAE	CONIDAE	
HABITAT	Ss	Si	Si	Ss	Si	Ss	Ss	Si	Si	Si	Rs	Rs	Rs
DISCOVERY BAY													
WHITES BEACH													
BRIDGEWATER BAY													
SHELLY BEACH (BRIDGEWATER)								●	●				
PORTLAND BAY												●	
CAPE REAMUR - PORT FAIRY			•	•				•				⬤	
THUNDER BEACH		•		•								●	
MOONLIGHT HEAD													
SHELLY BEACH (OTWAYS)		●	●						●			●	
APOLLO BAY - SKENES CK.											•	⬤	
KENNETT RIV - LORNE							•					●	
SWAN BAY & ENVIRONS							●						
BELLARINE PENINSULA													
NORTHWEST PORT PHILLIP BAY													
RICKETTS POINT - BEAUMARIS													
FRANKSTON - LONG ISLAND													
OROMANA - McCRAE													
TYRONE FORESHORE												●	
COLLINS BAY					•		●			•		⬤	
MUD ISLANDS										●			
NEPEAN OCEAN COAST		●										⬤	
FLINDERS		⬤										⬤	
SHOREHAM												●	
STONY POINT - YARINGA													
NORTHEAST WESTERNPORT													
WESTERN PHILLIP ISLAND	•			•						●		⬤	
SHELLY BEACH (SAN REMO)			●									⬤	
CAPE PATTERSON		⬤	•										
INVERLOCH													
WARATAH BAY							●						
WILSON'S PROMONTORY							●						
CORNER INLET													
NINETY MILE BEACH							●						
LAKES ENTRANCE							•						
PEARL POINT				●			⬤						
WINGAN INLET & ENVIRONS						•							
MALLACOOTA INLET & ENVIRONS				⬤			⬤						•

KEY TO SCALE OF
RELATIVE ABUNDANCE

Rare	1%	•
Occasional	1-10%	●
Frequent	10-45%	⬤
Very frequent	45%	⬤

TABLE 1 (Continued)

SPECIES IN SHELLY BEACHES ON THE VICTORIAN COAST.

Pelecypoda — Cephalopoda

Nototerebra albida	Bullaria botanica	Siphonaria diemenensis	Siphonaria tasmanica	Scaeoleda crassa	Anadara trapezia	Barbatia pistachia	Glycymeris flammeus	Tucetilla striatularis	Modiolus albicostus	Brachidontes rostratus	Mytilus planulatus	Electroma georgiana	Atrina tasmanica	Pecten alba	Camptonectes famigerator	Chlamys asperrimus	Monia ione	Ostrea angasi	Crassostrea commercialis	Neotrigonia margaritacea	Eucrassatella kingicola	Venericardia sp.	Fulvia tenuicostata	Phacosoma circinaria	Notocallista kingii	Sunemeroe aliciae	Tawera gallinula	Placamen placida	Bassina pachyphylla	Callanaitis disjecta	Gomphina undulosa	Eumarcia fumigata	Katelysia rhytiphora	Katelysia peronii	Pullastra galactites	Donacilla nitida	Notospisula parva	Mactra rufescens	Mactra australis	Mactra pura	Plebidonax deltoides	Soletellina biradiata	Pseudarcopagia victoriae	Homalina deltoidalis	Solen vaginoides	Pholas australasiae	Amplisepia apama	Argonauta nodosa	
TEREBRIDAE	BULLARIIDAE	SIPHONARIIDAE		LEDIDAE	ARCIDAE		GLYCYMERIDAE		MYTILIDAE			PTERIIDAE	PINNIDAE	PECTINIDAE			ANOMIIDAE	OSTREIDAE		TRIGONIIDAE	CRASSATELLIDAE	CARDITIDAE	CARDIIDAE	VENERIDAE												DONACILLIDAE	MACTRIDAE				DONACIDAE	SANGUINOLARIIDAE	TELLINIDAE		SOLENIDAE	PHOLADIDAE	SEPIIDAE	ARGONAUTIDAE	
Ss	Ss	Ri	Ri	Ss	Ss	Rs	Ss	Ss	Rs	Ri	Ri	Ss	Ss	Ss	Ss	Ss	Rs	Si	Ri	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Ss	Si	Si	Ss	Si	Si	Ss	Ss	Ss	Ss	Ss	Ss	F	F	HABITAT
										●				•			•						•						●												●						●		
										●																													•								●		
			•							•																			●									●	●										
								•		•																												●	●		•								
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	●				●					•	●	●		•				•					●									•	●		•		●					•	•	•					
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					●		●	●						•							•					•								•			•				•					•			
					•		•	•								•										•																			•			
							●	●											●										●								•				•						•		
					•		●	●								•	•	•	●										●			●					•				●			●		•	•	•	

NB. Taxonomy follows that of Macpherson and Gabriel (1962).

KEY TO HABITAT TYPE
OF EXTANT SPECIES

Rocky substrate:	intertidal	Ri
	subtidal	Rs
Soft substrate:	intertidal	Si
	subtidal	Ss
Free swimming:		F

S

summarized in Table 1. The shells have been classified by family and genus, and to species level wherever possible. It should be noted that speciation of fragmented and worn shell fragments is often difficult; in cases where it was difficult to identify shell species because of minor variations in shell sculpture, colour, and form these have been classified to genus level only. The data presented in Table 1 should not be taken as an exhaustive guide to the distribution of molluscs on the Victorian coast, but rather as data representative of the typical collections and major components of shelly beaches at specific localities.

The species content of shelly beaches is variable along the coast; some of the common assemblages and distribution trends can be obtained from the Table. Generally the shorelines west of Wilsons Promontory have more rocky habitats and more shelly beaches. Shell accumulations on the east coast, particularly of large pelecypods, are localized. The tendency for gastropods to be found on high wave energy rocky shorelines and pelecypods in sheltered areas and on sandy beaches is common.

Gastropod species such as *Haliotis ruber* (Shepard 1973) and *Cellana tramoserica* (Sowerby 1825) are commonly distributed on high wave energy rocky shorelines, as are members of the families Cymatidae, Thaidae and Buccinidae. The families Trochidae and Turbinidae are abundant in two areas: the rocky shorelines between Cape Bridgewater and Lorne, and the Nepean Peninsula, Phillip Island and Cape Patterson. In comparison the Potamididae are frequent in sheltered low wave energy areas such as the western shores of Port Phillip Bay, northeastern Westernport Bay and East Gippsland estuaries, while the Scalidae are more frequent on the western Victorian coast.

Pelecypods often accumulate in high concentrations. The Mactridae are very frequent in shelly beaches on high wave energy sandy shorelines on the far west coast; this family is replaced by the Glycimeridae in similar environments on Gippsland shores. The Mytilidae are most frequent in the west on both rocky open coasts and sheltered shorelines; the Veneridae are centred on low wave energy environments of Port Phillip Bay and Westernport Bay.

The free swimming Cephalopods of which *Amplisepia apama* (Gray 1849) and *Argonauta nodosa* (Solander 1786) are the most common, are distributed along most of the Victorian coastline.

CONCLUSION

Although infrequent, shelly beaches are present on the Victorian coast in sectors where sufficient quantities of biogenic material are available for incorporation in beaches. The availability of shell material is related to the population density of contributing species. The nature of the material depends on the molluscan faunal assemblage present, which is in turn determined by the types of habitat available in the area, and the degree of fragmentation and abrasion of the shells. Shelly material accumulates on beaches in response to a variety of wave conditions; reduced wave height after refraction produces the swash which often causes accumulation of shelly debris. In some environments, particularly estuaries and shallow embayments, storm waves cause accelerated accumulation, and pile shell material in deep strands.

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TRACE ELEMENT ANALYSIS OF ABORIGINAL GREENSTONE ARTEFACTS

To Discriminate Between the Sources, Mount Camel and Mount William in Southeastern Australia

By A. L. WATCHMAN* AND R. S. FREEMAN†

ABSTRACT: As rocks at the Mount William and Mount Camel Aboriginal greenstone artefact quarries in central Victoria are not readily differentiated by macroscopic and microscopic features, geochemical studies were carried out. Trace element analyses were determined for twenty samples from the quarries and seventy-one artefacts. Using this method to find distinguishing attributes between quarries we are able to determine the sources of most artefacts.

INTRODUCTION

In a study of greenstone artefacts in south-eastern Australia McBryde and Watchman (1976) distinguished between rock types quarried at several locations in Victoria (for example, Howqua, Geelong, Hopkins River and Jallukar), but could not differentiate material from the Mount William and Mount Camel areas. The lithologies from these two sites are so similar that hand examination, measurements of density, petrological studies and x-ray diffraction methods cannot reveal distinguishing attributes. Rock types from the other quarries are easily distinguished from each other, and from Mount William and Mount Camel, thereby allowing allocation to sources without geochemical analyses.

A small area of the Mount William quarry contains a characteristic white-spotted amphibole hornfels, a rock type not found at Mount Camel. Artefacts composed of this lithology are therefore assigned to Mount William.

Useful petrographic attributes for source characterization in some rocks from Mount Camel are small plates of diopside, amphibole pseudomorphs, relict tuffaceous texture and carbonate and epidote veins. Otherwise there is little difference between amphibole hornfelses at Mount William and Mount Camel. As not all the artefacts examined in this study could be sourced using these petrographic features we decided to use statistical evaluations of geochemical data to characterize each quarry and then fit the artefacts to a specific source.

The method of trace element analysis was selected for discrimination purposes because it is relatively simple, less involved than major element analysis, and because similar techniques have proved successful in solving other archaeological problems: for example Cann *et al.* (1969), Ward (1974), Sigleo (1975). Preliminary trace element analyses of artefacts and quarry materials indicate that several elements could be used to discriminate between sources of amphibole hornfelses. In this paper the method of analysis, statistical evaluations and problems involved in allocating each artefact to a specific source are discussed.

PETROGRAPHY

The Mount William and Mount Camel Aboriginal artefact quarries lie along the Mount William-Heathcote-Colbinabbin Greenstone Belt (Fig.1). This belt is composed of basic metavolcanics and altered pyroclastics (Skeats 1908, Thomas & Singleton 1956).

At Mount William exploitation of outcrops and stone working activity was carried out diagonally across the Lower Unit of the Cambrian Heathcote Greenstone. The Lower Unit is almost vertical in

*Department of Prehistory and Anthropology, Australian National University, P.O. Box 4, Canberra, A.C.T. 2600.
†Department of Geology, Australian National University, P.O. Box 4, Canberra, A.C.T. 2600.

the quarry area and consists essentially of amphibole hornfels (impure nephrite, Gregory 1903), up to five hundred m thick. The unit is characterized by spheroids filled with quartz, carbonate, and albite, the interlocking amphibole needles forming a decussate texture. Rocks quarried for artefacts are generally green to black and strongly recrystallised.

Two small areas near Mount Camel were worked in outcrops of the Heathcote Greenstone along strike for 200 m over a width of 30 m and on a knoll about 100 m in diameter. In the Mount Camel region metavolcanics, metadolerite and small lenses of chert comprise the Heathcote Greenstone. Rocks were quarried in metavolcanics and consist predominantly of actinolite and cummingtonite with minor amounts of albite, carbonate and epidote. They contain spheroids filled by quartz and albite, and strongly resemble similar features found in rocks at Mount William. In general the artefacts are green to brown and have decussate texture.

Rocks in the two quarry areas are petrographically similar because they share the same geological histories (Skeats 1908, Thomas & Singleton 1956). After extrusion of an extensive area of volcanics, the parent rocks of the Heathcote Greenstone, post-consolidation and metamorphic processes affected the primary minerals and textures. The metavolcanics are of Alpine-type ultramafic affinity and geochemically similar to olivine pyroxenite (Watchman 1977). At Mount William isochemical contact metamorphism took place whereas in the Mount Camel area the rocks were metasomatised.

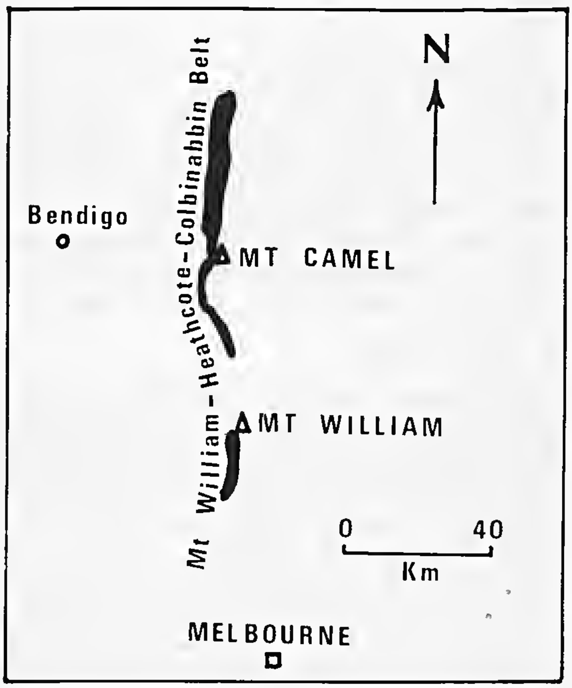

FIG. 1 — Locality map showing the positions of the Mount William and Mount Camel Aboriginal greenstone axe quarries.

GEOCHEMICAL METHODS

Rock samples from the quarry sites and slices taken out of artefacts were crushed to fine powders using a tungsten lined Seibtechnic grinding mill. The powders were then pressed into pellets for subsequent x-ray fluorescence analysis (Norrish & Chappell 1967). All analyses were carried out on a Philips PW 1220 X-ray Fluorescence Spectrometer. Rubidium (Rb), strontium (Sr), yttrium (Y) and lead (Pb) were measured with a molybdenum target x-ray tube using a scintillation counter, LiF_{200} analysing crystal and coarse collimator. Zirconium (Zr), niobium (Nb), nickel (Ni), copper (Cu) and zinc (Zn) were determined under similar conditions but with a tungsten target x-ray tube. Mass absorption coefficients were measured for each sample and corrections made for interelement effects, instrument drift, and detector dead time. Concentrations of trace elements in quarry materials are given in Table 1 and for the artefacts in Table 2.

METHODS OF DISCRIMINATION

After analysis of rocks from the quarries and artefacts, the problem was to try to fit the concentration of trace elements of each of the artefacts with the concentration of similar elements in samples of raw material from the quarries. Fig. 2 shows the ranges in trace element values for rocks from each quarry and of the population of artefacts. Binary and ternary diagrams (Figs.3-6) are used to illustrate the wide variation in several trace elements. Since all the specimens were petrographically similar and had proven indistinguishable in earlier studies, statistical tests were applied to determine differences in chemistry between quarry samples.

To find a disparity in the trace element chemistry of samples from each quarry a statistic, called the similarity coefficient, was computed for all quarry materials, using average trace element contents. This statistic was calculated according to the method of Borchardt *et al.* (1972), in which a simple equation is evaluated. At the ninety-five per cent confidence level, similarity coefficients of greater than 0.800 indicate excellent correlation between samples and when less than 0.560, a pair of

samples are probably derived from different sources (Sigleo 1975). Results of this test for Mount William (d_w) and Mount Camel (d_c) are listed in Table 3.

A multivariate statistical test was devised, following Rao (1973, p.577-579), in which a linear discriminant function similar to Mahalanobis's distance was evaluated. This test is used to classify an artefact according to the statistical significance of the fit of trace element contents in each artefact compared with average concentrations of elements in quarry samples. Essentially the method is to take the means of trace element values, calculate the covariance sums of squares matrices and evaluate a complex quadratic equation. The order of testing is to find whether a sample fits either a new population (P_{new}) or one of P_1 (Mount William) and P_2 (Mount Camel). When any test is significant at the five per cent level the sample is assigned to that population and another sample is then tested. Two additional cases may also arise and these need to be briefly mentioned.

When a sample fits both P_1 and P_2 it is evidence that the artefact is representative of a 'special' p_{new} which is between P_1 and P_2. On the other hand if both tests for P_1 and P_2 are not significant this means that there is no clear-cut solution to the classification of the sample. Results of this testing procedure using raw data and their logarithmic transformations are listed in Table 3.

DISCUSSION

It is important to realise that to obtain effective source and artefact characterization the researcher should seek for the most easily recognized property of source material which can be determined in a routine manner. It may prove costly and ineffective to strive by complex analytical and computer techniques to try to establish attributes of material from a source when a relatively inexpensive, unsophisticated and rapid method is more practical.

Following these lines our investigation into sourcing studies of greenstone artefacts began by determining the simplest characteristic feature of quarry materials and matching attributes between them and artefacts. This method relies on being able to find features in artefacts which fit the

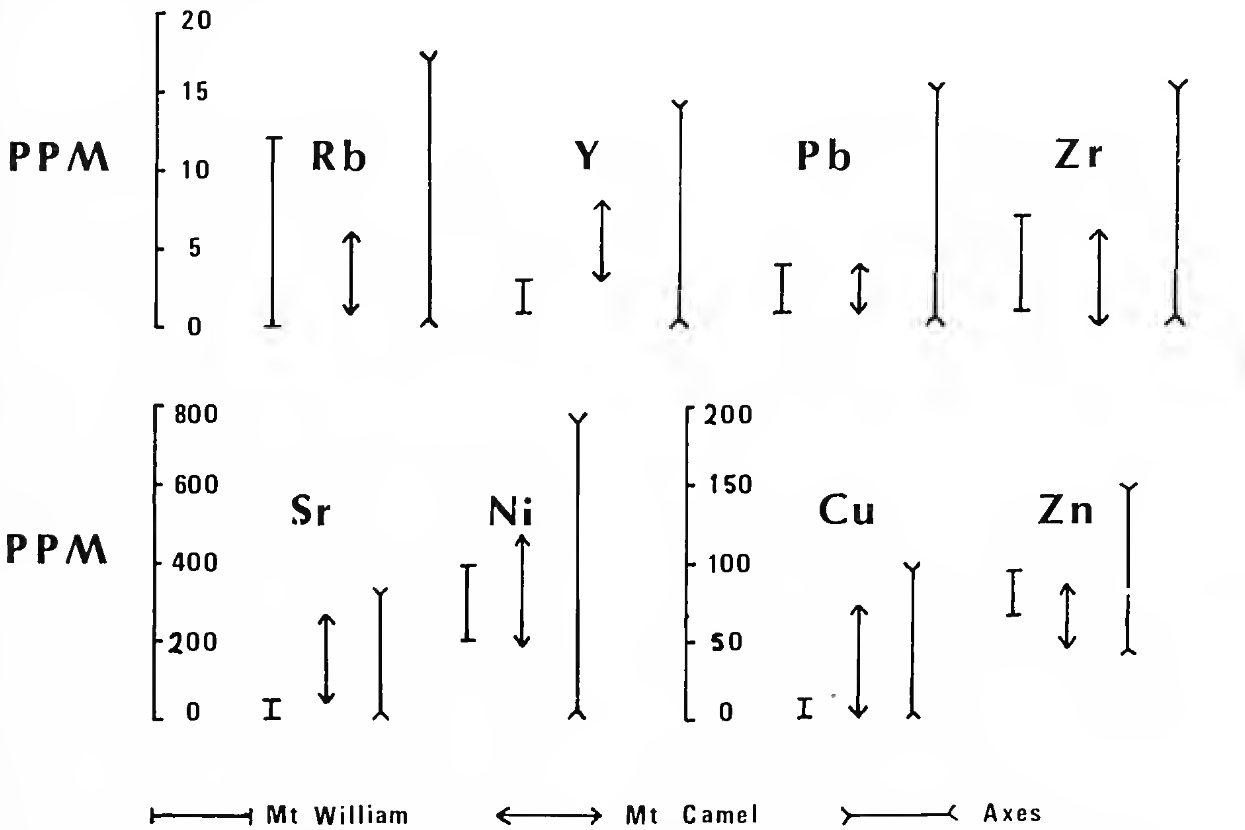

FIG. 2 — Ranges of trace element contents in quarry samples and axe-stones.

observed range of characteristic attributes of quarry samples. In some cases this is easily carried out, but in others an artefact cannot be assigned to a particular quarry. The principles involved in source characterization and allocation of artefacts to specific source areas have been discussed by De Bruin *et al.* (1976).

Artefacts from Mount William and Mount Camel have slightly different colours, textures and mineral assemblages. Pale brown axes are more likely to come from the quarry near Mount Camel whereas black artefacts are almost certainly derived from Mount William. However, the existence of a continuous spectrum from green-brown to green-black for all materials means that colour can be used only as an initial guide to the source of an artefact.

Most artefacts are fine-grained and compact, generally without features diagnostic of material from a particular quarry. The exception is the white-spotted hornfels consisting predominantly of actinolite with tiny aggregates of cummingtonite. This rock is easily recognised in hand specimen by its texture, which is similar to spotted hornfels shown by pelitic rocks in contact metamorphic terrains. This characteristic rock type is found only at Mount William; therefore artefacts composed of this lithology are certainly derived from that source.

Finding distinguishing attributes of the materials used for artefacts would not normally be expected to be as difficult as that found in the present study of amphibole hornfelses. Minor problems of source characterization have been overcome in dealing with obsidian, flint, soapstone and other lithologies using computer based statistical analyses of trace element concentrations. In this project, however, we have been unable to obtain for every specimen attributes which would clearly distinguish amphibole hornfelses of Mount William from those of Mount Camel.

Trace element analyses of seventy-one artefacts out of a total number of fifteen hundred have given us preliminary information from which tentative source allocations can be made. There is a strong possibility that major element values can be used to differentiate between these two sources, but considerable time and expense will be needed to verify this conclusion.

Concentrations of Rb, Pb, Zr, Ni, Cu and Zn in amphibole hornfelses from the two quarries are similar (Fig.2). On the other hand, values for y and Sr do not overlap and therefore these elements are possible discriminants. The range of trace element concentrations in the population of artefacts, when compared with the spread shown by quarry samples, leads to two possible explanations.

The wider range of values in artefacts may result either from poorly representative quarry samples or because petrographically comparable material is available from another (as yet unknown) source. Both possibilities together may contribute to the observed ranges for Y and Sr in the artefact population. Under these circumstances the allocation of artefacts to sources based on Y and Sr must be treated with reservation.

Discrimination between sources is illustrated in Figs. 3-6. Covariance relations between Y and both Sr and Zr enable classification of most artefacts because there are significant differences between these elements for samples from the quarries. Y is apparently the most effective discriminant, being present in Mount William artefacts below three parts per million and in greater amounts in Mount Camel samples.

Ternary diagrams (Figs. 5, 6) also illustrate differences and similarities between samples from the two quarries. Even though quarry materials are easily separated from each other the addition of components which are not good discriminants themselves leads to a decrease in the effectiveness of source characterization. Consequently Y is the best single discriminant of all the elements determined.

Results of the two statistical methods do not promise any more than can be obtained by using Y. The application of multivariate analysis to geochemical data obtained from archaeological specimens has been useful in classifying sources of artefacts; for example Hodson (1969), Ward (1974) and Bieber *et al.* (1976). So then why does the multivariate approach fail in this case?

Multivariate analysis of geochemical data to characterize different sources is based on several assumptions. Each source is thought of as being geochemically homogeneous with normally distributed trace element values. Different sources are considered to have clearly separate ranges in their trace element concentrations.

The statistical methods do not decisively identify the distinguishing attributes in rocks from each source because of the inhomogeneity of the formations quarried. Multivariate analysis is not applicable in this case to classify sources of artefacts because of the geochemical similarity of source materials (that is, the ranges of values overlap), trace element concentrations in quarry samples are skewed and not normally distributed, the geochemistry of the artefact population is not bimodal, and unknown sources may contain petro-

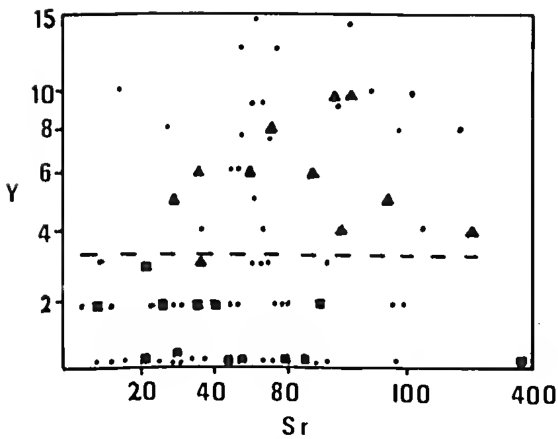

FIG. 3 — Plot of Y against Sr for Mount William (squares), Mount Camel (triangles) quarry materials and axe-stones (circles).

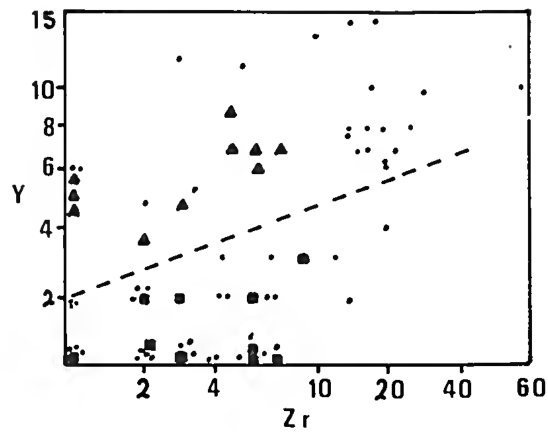

FIG. 4 — Plot of Y versus Zr for quarry materials and axe-stones (same symbols as Fig. 3).

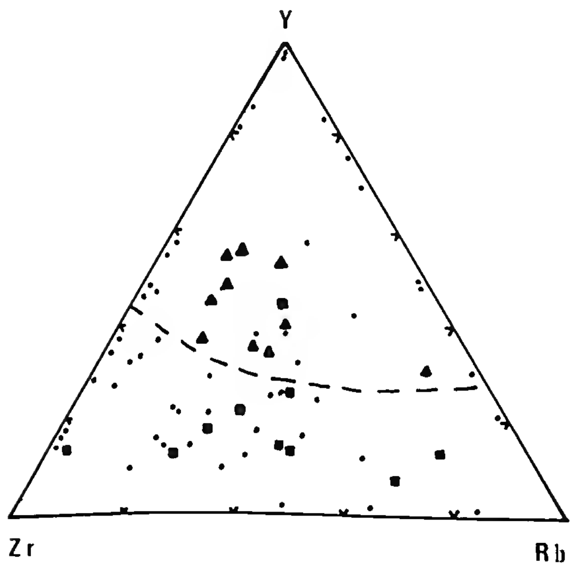

FIG. 5 — Relation between Y-Zr-Rb for quarry samples and axe-stones (same symbols as Fig. 3).

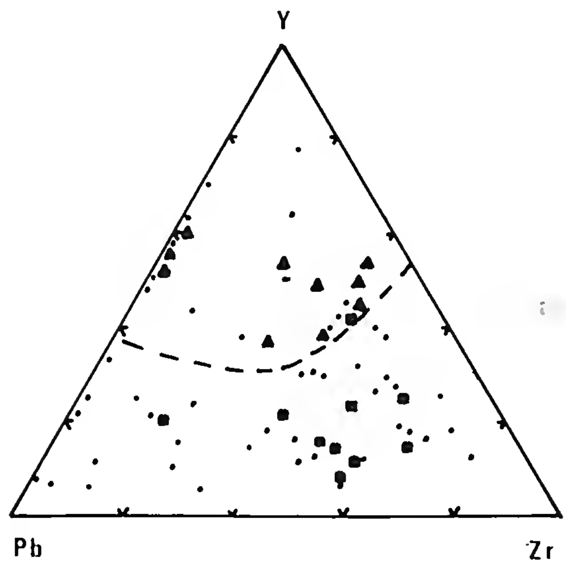

FIG. 6 — Relation between Y-Pb-Zr for quarry samples and axe-stones (same symbols as Fig. 3).

graphically and geochemically comparable material which have not been taken into consideration.

Amphibole hornfelses at Mount William and Mount Camel contain different amounts of Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O and P_2O_5 (Table 1). These are possible attributes suitable for source and artefact characterization. We have not analysed artefacts for major elements because the x-ray fluorescence technique available to us is not a rapid, cheap routine method. Another simpler method, preferably non-destructive, such as non-dispersive x-ray fluorescence, is needed to analyse the large number of artefacts in collections.

CONCLUSION

This study has shown that source discrimination of Aboriginal artefacts from the Mount William and Mount Camel quarries is not always effective using trace element analysis alone. However, it is possible using selected trace elements (Y,Sr,Zr), combined with megascopic and microscopic features to characterize the quarry materials and thereby allocate artefacts to a specific quarry. It should be emphasised that when sourcing artefacts from sites with similar geological histories it is essential to understand and appreciate the geological processes which have affected the rocks. From our study we are able to determine the sources of most of the artefacts analysed for trace elements.

ACKNOWLEDGMENTS

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TABLE 1

SELECTED MAJOR AND TRACE ELEMENT ANALYSES OF AMPHIBOLE HORNFELSES FROM QUARRIES AT MOUNT WILLIAM AND MOUNT CAMEL

	Mount William			Mount Camel		
SiO_2	54.47	55.84	51.20	50.08	50.12	50.78
TiO_2	.03	.03	.01	.12	.22	.20
Al_2O_3	3.26	3.08	1.29	5.83	9.28	8.99
Fe_2O_3	5.20	3.04	6.13	2.17	2.14	1.74
FeO	7.25	8.73	4.85	5.47	6.61	6.83
MnO	.18	.17	.24	.24	.18	.17
MgO	22.85	23.75	24.12	11.06	14.37	13.83
CaO	3.92	2.29	5.80	22.05	14.54	14.99
Na_2O	.19	.20	.22	.35	.59	.51
K_2O	.07	.02	.01	.26	.07	.05
P_2O_5	.01	.01	.01	.07	.03	.04
S	–	–	–	.01	.01	.01
H_2O+	2.39	2.42	3.67	1.09	1.77	1.82
H_2O-	.05	.07	.08	.07	.05	.07
CO_2	.05	.04	1.65	1.07	.09	.08
TOTAL	99.92	99.69	99 28	99.93	100.07	100.10
Rb	5	2	1	1	2	2
Sr	348	52	72	37	46	25
Y	7	6	6	6	1	7
Pb	5	5	5	3	3	3
Zr	29	14	18	27	11	10
Nb	–	–	1	–	–	–
Ni	522	272	398	479	491	395
Cu	2	45	4	3	3	6
Zn	114	93	82	109	91	92

TABLE 2

TRACE ELEMENT CONTENTS IN AMPHIBOLE HORNFELS ARTEFACTS

Axe No.	Rb	Sr	Y	Pb	Zr	Nb	Ni	Cu	Zn
162	1	58	8	2	10	1	698	24	77
163	0	101	1	10	0	0	292	6	186
166	0	74	2	10	4	0	245	3	83
170	0	30	7	6	9	0	1000	31	76
187	1	17	2	2	6	1	257	4	103
190	1	47	7	6	10	0	748	27	82
196	1	36	1	3	2	0	344	3	79
198	3	37	1	3	5	0	262	30	95
205	0	17	1	3	2	0	319	8	81
209	2	188	2	1	0	0	352	5	82
221	1	29	1	3	3	0	304	3	71
225	2	55	2	5	1	0	384	15	72
227	0	244	3	3	0	0	260	3	62
258	3	73	2	4	2	0	220	37	83
264	0	43	6	6	1	0	84	59	69
270	0	75	12	1	3	0	80	83	70
279	2	24	2	5	6	0	278	63	81
280	1	65	8	5	12	0	682	33	81
281	0	14	1	15	2	0	546	16	51
297	2	15	1	3	2	0	346	4	83
303	16	55	16	15	20	1	117	98	108
327	0	55	5	3	3	0	227	19	77
331	1	63	7	3	15	2	244	11	89
338	2	14	3	6	6	1	199	5	89
343	0	295	7	4	0	0	200	5	76
346	0	114	8	6	8	1	688	3	70
351	0	38	1	3	1	0	263	8	78
359	1	44	2	5	1	0	399	3	67
363	0	109	3	36	2	1	222	13	77
398	8	93	13	6	11	1	97	75	80
409	1	29	1	2	2	0	471	4	75
411	8	199	7	3	0	1	731	28	65
412	0	99	2	1	11	0	409	9	58
419	2	79	1	7	0	0	345	10	81
424	3	32	2	1	2	0	393	5	81
435	0	51	12	3	5	0	64	47	77

TABLE 2 (Continued)

TRACE ELEMENT CONTENTS IN AMPHIBOLE HORNFELS ARTEFACTS

Axe No.	Rb	Sr	Y	Pb	Zr	Nb	Ni	Cu	Zn
474	1	38	1	4	0	0	412	3	62
479	2	65	1	6	1	0	309	4	74
484	1	128	16	10	15	1	146	18	64
485	0	59	1	7	4	0	265	3	156
542	2	66	3	3	10	0	270	31	71
544	0	66	4	2	15	1	376	7	59
547	0	42	6	6	1	0	97	93	64
552	3	69	3	10	4	0	366	2	86
560	6	65	1	6	2	0	365	9	95
572	4	44	2	8	2	0	340	27	73
575	0	20	2	4	3	0	313	1	67
576	7	90	13	3	19	1	75	110	57
577	2	106	13	40	12	1	139	57	109
579	4	148	1	4	0	0	281	25	69
588	1	51	2	2	0	0	368	7	69
589	0	37	2	2	1	0	399	4	70
590	1	204	2	4	2	0	267	186	53
592	2	17	1	3	3	1	404	1	73
602	1	72	3	2	0	1	236	38	40
605	0	79	1	3	0	0	313	15	64
607	1	36	0	2	1	0	304	2	67
608	0	78	2	2	0	0	288	2	64
609	0	112	1	2	0	0	314	4	75
610	1	59	1	8	1	0	261	7	68
611	6	35	0	1	1	0	434	1	71
615	2	187	1	4	0	0	291	7	63
623	0	12	2	1	2	0	363	14	56
624	0	47	1	3	5	0	288	2	67
625	4	105	8	4	16	1	242	127	96
627	1	23	1	4	6	1	232	2	80
628	2	207	10	8	0	1	155	3	81
629	4	27	0	2	2	0	436	1	68
630	0	27	1	1	4	0	309	7	71
634	4	143	10	4	19	1	236	6	99
643	3	30	2	3	4	0	310	5	75

TABLE 3

SUMMARY OF RESULTS OF THE SOURCE DISCRIMINATION METHODS:

Axe No.	Hand examn. & petrology	From Figs. 2, 3, 4.	Similarity co-efficients d_w	d_c	Statistical tests raw	log	Final
MW162	W/C	C	.428	.617	new	new	C
163	"	W	.510	.371	"	"	W
166	"	W	.537	.503	"	"	W
170	C	C	.447	.469	"	"	C
187	W/C	W	.587	.491	"	"	W
190	"	C	.455	.569	"	"	C
196	"	W	.740	.582	W	W	W
198	W	W	.753	.642	W	W	W
205	W/C	W	.707	.529	W	W	W
209	"	W	.526	.518	new	new	W
221	"	W	.811	.637	W	W	W
225	"	W	.617	.725	W	W	W
227	"	W	.420	.484	new	C	C
258	"	W	.675	.674	"	W-C	W-C
264	"	C	.388	.469	"	new	C
270	W/C	C	.369	.508	"	"	C
279	"	W	.659	.603	"	W	W
280	"	C	.443	.578	"	new	C
281	"	W	.500	.414	"	"	W
297	"	W	.759	.615	W	W	W
303	"	C	.296	.327	new	new	C
327	C	C	.567	.766	C	C	C
331	C	C	.515	.648	new	new	C
338	W/C	W	.628	.549	"	"	W
343	"	C	.464	.441	"	"	C
346	C	C	.407	.479	"	"	C
351	W/C	W	.684	.506	W	W	W
359	"	W	.592	.531	W	W	W
363	"	W	.445	.547	new	new	W-C
398	"	C	.385	.474	"	"	C
409	"	W	.721	.479	W	W	W
411	"	C	.359	.570	new	new	C
412	W	W	.436	.495	"	"	W-C
419	"	W	.630	.590	"	"	W
424	"	W	.736	.535	"	"	W
435	W/C	C	.416	.514	"	"	C

NOTE:

d_w, d_c: similarity coefficients of axes compared to average trace element values of Mount William and Mount Camel respectively. W — Mount William, C — Mount Camel, W/C Mount William/Mount Camel undifferentiated.

TABLE 3 (Continued)

SUMMARY OF RESULTS OF THE SOURCE DISCRIMINATION METHODS:

Axe No.	Hand examn. & petrology	From Figs. 2, 3, 4.	Similarity co-efficients d_w	d_c	Statistical tests raw	log	Final
474	W/C	W	.640	.462	W	W	W
479	W	W	.713	.607	W	W	W
484	W/C	C	.358	.536	"	"	C
485	"	W	.587	.434	"	"	W
542	"	C	.561	.767	"	"	C
544	C	C	.475	.556	"	"	C
547	W/C	C	.381	.454	"	"	C
552	"	W	.621	.598	"	"	W
569	W	W	.595	.490	W	W	W
572	W	W	.666	.560	new	new	W
575	W/C	W	.575	.490	W	W	W
576	"	C	.350	.456	new	new	C
577	W	C	.300	.442		"	C
579	W/C	W	.473	.530	"	"	W–C
588	"	W	.558	.536	W	W	W
589	"	W	.555	.468	W	W	W
590	"	W	.530	.565	new	new	C
592	"	W	.731	.641	"	"	W
602	"	C	.378	.561	"	"	C
605	W/C	W	.537	.593	W	W–C	W–C
607	"	"	.519	.498	"	W	W
608	"	"	.435	.490	"	W–C	W–C
609	"	"	.543	.467	"	W	W
610	"	"	.657	.529	new	new	W
611	"	"	.460	.387	W	W	W
615	"	"	.682	.580	new	W–C	W–C
623	"	"	.476	.486	W	new	W
624	"	"	.640	.544	"	W	W
625	"	C	.500	.569	new	new	C
627	"	W	.713	.486	"	"	W
628	"	C	.423	.472	"	"	C
629	"	W	.572	.485	W	W	W
630	"	"	.709	.483	"	"	W
634	"	C	.598	.532	"	new	W–C
643	"	W	.842	.661	new	"	W

FIRST RECORD OF *Richardsonianus australis* (BOSISTO, 1859) (HIRUDINEA: RICHARDSONIANIDAE) TAKING A BLOOD MEAL FROM A FISH

By P. L. CADWALLADER*

ABSTRACT: *Richardsonianus australis* (Bosisto) is recorded for the first time taking a blood meal from a fish. Leeches were found on three of 130 *Galaxias olidus* Günther (Family Galaxiidae) taken in a small, steep tributary of the Seven Creeks river system, Victoria. Twenty-two fish in the sample had characteristic leech scars; 16 had single scars, 3 had two scars and 3 had three scars. Most of the scars were on the upper surface of the body and in front of the pelvic fins insertion. The length to caudal fork of scarred fish varied from 51 to 95 mm, that of unscarred fish from 24 to 87 mm. The sex ratios for scarred and unscarred fish did not differ significantly ($P > 0.1$) from 1:1. The probable mechanism of attachment of the leeches to the galaxiids is discussed.

INTRODUCTION

Richardsonianus australis was first described by Bosisto in 1859 (Bosisto 1859), but since then very little information has been published on its biology. It was originally described as *Hirudo australis* and was subsequently renamed *Limnobdella australis* before being placed in *Richardsonianus*. The history of its taxonomy is to be found in Soós (1968) and Richardson (1968, 1969). It is an essentially aquatic leech which has been recorded feeding on the blood of humans and other mammals (Pope 1965) and is known to feed on turtles and frogs (Richardson, pers. comm.). This note presents details of the finding of *R. australis* parasitising a scale-less freshwater fish, *Galaxias olidus* Günther (Family Galaxiidae), and is the first record of *R. australis* taking blood meals from fish.

COLLECTION OF THE MATERIAL

A survey of the fish fauna of the Seven Creeks river system, Victoria, was undertaken during the summer of 1975-76, when fish were collected at 60 sampling stations throughout the system, from headwater tributaries to near the point where the main Seven Creeks channel enters the Goulburn River. At one of the sampling stations (1:100 000 Topographic Survey, Sheet 8024, Series R652, Map Reference CV841207) leeches, subsequently identified as *R. australis*, were found attached to three individual *G. olidus*, one leech being attached

PLATE 27
Galaxias olidus (LCF 91 mm) with two leech scars.

*Fisheries and Wildlife Division, Snobs Creek Freshwater Fisheries Research Station and Hatchery, Private Bag 20, Alexandra, Victoria 3714.

to each galaxiid. Many other galaxiids in the sample had Y-shaped scars (Pl. 27) typical of the incisions made by 3-jawed sanguivorous leeches. No other fish species were recorded at this sampling station. *Galaxias olidus* was recorded at 21 other stations, at 12 of which it was the only fish species recorded, but no leeches or leech scars were found on these galaxiids or on any of the other fish species taken in the Seven Creeks survey (Table 1). A detailed report of the Seven Creeks survey will be published at a later date.

The sampling station in question was on a small (mean width 1 m, mean depth 0.4 m) steep-gradient (50 m/km) tributary at an altitude of 540 m. The substrate was composed of sand, and debris, mainly fallen branches, was abundant on the stream bed. *Callitriche* and *Veronica* were the predominant aquatic plants in the sampling area, and the stream was well shaded by eucalypts, wattles and overhanging fern-covered banks.

The fish sample was taken by means of rotenone poisoning between 1020 and 1115 h on 16 December 1975. A stop net was set across the stream and rotenone (together with fluorescein to indicate its spread) was added to the water about 120 m upstream. Potassium permanganate was added to the stream at the stop net to neutralise the effect of the poison. Fish were collected at the stop net and throughout the poisoned stretch of stream by means of small-mesh (>1.05 mm) dip nets. The three leeches attached to the fish became detached when the fish were removed from the water.

TABLE 1

FISH SPECIES RECORDED IN THE SUMMER 1975-76 SURVEY OF THE SEVEN CREEKS RIVER SYSTEM.

Family	*Species*
Percichthyidae	*Maccullochella maquariensis* (Cuvier and Valenciennes)
	Macquaria australasica Cuvier and Valenciennes
	Plectroplites ambiguus (Richardson)
Teraponidae	*Bidyanus bidyanus* (Mitchell)
Kuhliidae	*Nannoperca australis* Günther
Gadopsidae	*Gadopsis marmoratus* Richardson
Galaxiidae	*Galaxias olidus* Günther
Retropinnidae	*Retropinna semoni* (Weber)
Gobiidae	*Hypseleotris klunzingeri* (Ogilby)
Salmonidae	*Salmo trutta* Linnaeus
Percidae	*Perca fluviatilis* Linnaeus
Cyprinidae	*Cyprinus carpio* Linnaeus
	Carassius auratus (Linnaeus)
Poeciliidae	*Gambusia affinis* (Baird and Girard)

THE MATERIAL

Of 130 *G. olidus* collected, 22 had characteristic leech scars; 16 fish had single scars, 3 had two scars and 3 had three scars (Fig. 1). Of the 31 scars, 15 were on the dorsal surface, 8 on the dorso-lateral surface, 4 on the ventro-lateral surface and 4 on the ventral surface; 23 scars were in front of the pelvic fins insertion and 8 were behind the pelvic fins insertion. The LCF (length to caudal fork) of scarred fish varied from 51 to 95 mm (mean 67 mm), whereas that of unscarred fish varied from 24 to 87 mm (mean 61 mm). The sex ratios for scarred and unscarred fish did not differ significantly from 1:1 (Table 2); the sex of each fish was determined by microscopic examination of the gonads.

DISCUSSION

Richardsonianus australis is not common in fast-flowing waters where the substrate is composed of gravel or boulders, but in waters with a substrate of sand or mud and with plenty of shelter, such as fallen branches, densities may reach one leech/ $10m^2$ of substrate (Richardson, pers. comm.). Conditions conducive to high leech densities occurred at the Seven Creeks station where the leech-scarred galaxiids were found. In addition, the station was situated above a pool which would probably serve as a refuge for both leeches and galaxiids during dry periods. Although similar conditions occurred at other Seven Creeks stations where galaxiids and other fish species occurred no leech-scarred fish were found at these stations.

Many leeches live as ectoparasites on fish (Meyer 1940, 1946a, 1949, 1965) and may even reach epidemic proportions (Meyer 1946b). Brook trout, *Salvelinus fontinalis* (Mitchill) have been killed as the result of attacks by hordes of the freshwater leeches *Macrobdella decora* (Say) and *Haemopis grandis* (Verrill) (Rupp and Meyer 1954). *Richardsonianus australis* is a competent swimmer and actively seeks its hosts (Richardson, pers. comm.). It is likely that it attaches itself to *Galaxias olidus* in a manner similar to that

TABLE 2

SEX RATIOS OF *Galaxias olidus* TAKEN IN THE PRESENT STUDY

	Males	*Females*	X^2 *(d.f. = 1)*	*Significance*
Unscarred	48	60	1.3333	P>0.1
Scarred	14	8	1.6364	P>0.1
Total	62	68	0.2769	P>0.5

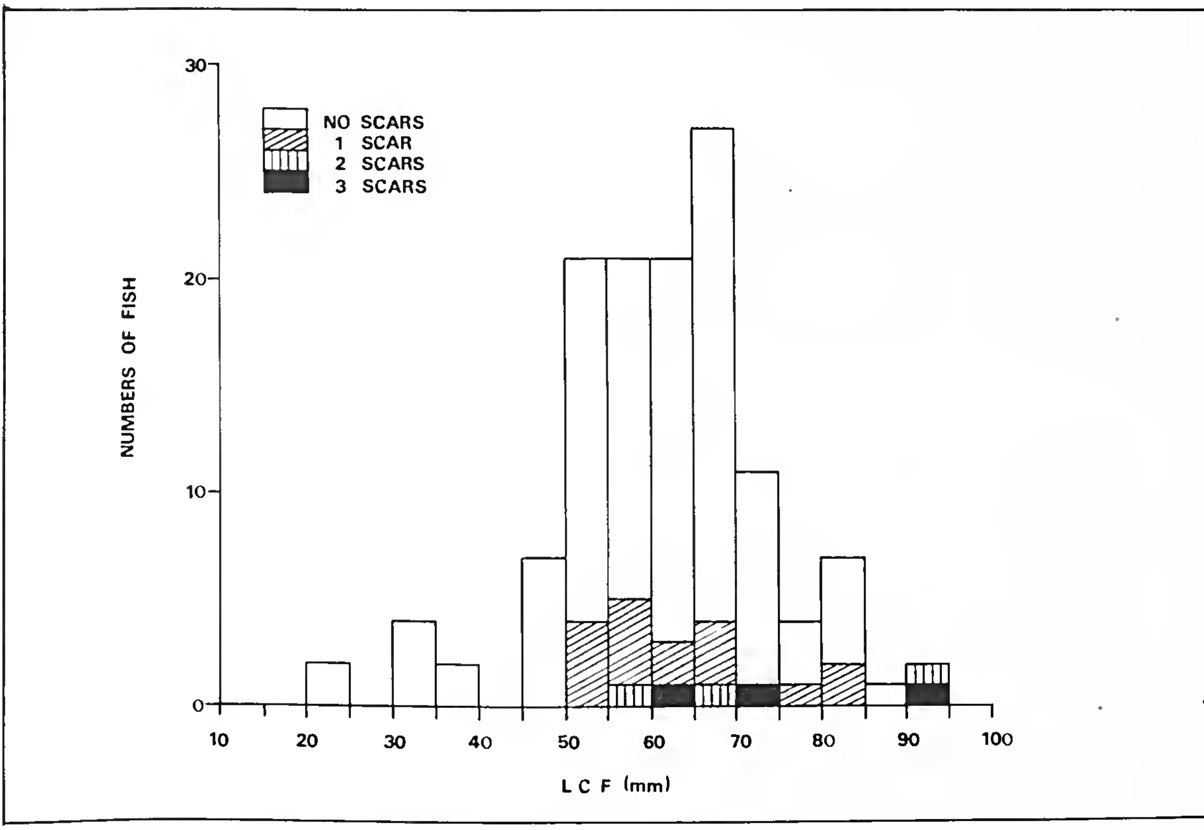

FIG. 1 — Length frequency distribution of *Galaxias olidus*, showing the numbers of fish of different lengths having no scars, one scar, two scars and three scars.

employed by *Kaiyabdella dawbini* (Richardson). This leech actively seeks its host *Goddardobdella elegans* (Grube), another leech, swimming to it and attaching rapidly and securely to it by the anterior sucker. This is done while both are swimming (Richardson 1972). This method of attachment is in contrast to that of *Calliobdella nodulifera* (Malm), which is incapable of swimming. This marine leech attaches itself by the posterior sucker to some suitable object and, extending itself, sways to and fro. With the anterior sucker it strikes and fixes upon a passing fish with remarkable speed and, releasing its hold posteriorly, is carried off attached to its host (Leigh-Sharpe 1917, quoted by Meyer 1946b).

In *G. olidus* the majority of the scars were on the upper surface of the body and anterior to the pelvic fins insertion. Such positioning would make it difficult for the fish to displace the leech by rubbing against the bottom or debris, etc., the method which fish commonly use to clear away objects attached to the body.

Attacks by *R. australis* on fish must be considered exceptional since of the 14 species of fish recorded at the 60 Seven Creeks sampling stations only one species, *G. olidus*, was attacked and then only at one station, although this particular species also occurred at 21 other stations.

ACKNOWLEDGMENTS

I am grateful to Professor L. R. Richardson for identifying the leeches, for providing unpublished information on the ecology of *R. australis*, and for his comments on the manuscript. I thank Messrs R. K. Donald, M. Smith and A. K. Morison for assistance with the collecting and processing of the galaxiids, Mr. J. Cooper who took the photograph of the leech-scarred galaxiid, and Dr D. D. Evans for his comments on the manuscript.

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THE LATE PLEISTOCENE AND HOLOCENE HISTORY OF THE MIDLANDS OF TASMANIA, AUSTRALIA: POLLEN EVIDENCE FROM LAKE TIBERIAS

By M. K. MACPHAIL* AND W. D. JACKSON*

ABSTRACT: During the late Pleistocene, markedly cold and dry climates in the Tasmanian central Midlands limited vegetation to sparse, treeless grasslands or possibly a chenopod steppe. Increases in temperature and effective precipitation between *c.* 11,000–9,000 B.P. resulted in the replacement of much of this vegetation with *Eucalyptus*-dominated formations. The ensuing vegetation, probably a mosaic of dry sclerophyll forest, woodland and grassland, has remained characteristic of the region up to the present.

Changes in the understory flora of *Eucalyptus* forests believed to be some distance from Lake Tiberias imply climates in the early to mid-Holocene slightly wetter than at present. This phase was followed by a reversion towards drier conditions leading to the modern subhumid climate. The pollen evidence is against previous concepts of mid-Holocene aridity in eastern Tasmania.

INTRODUCTION: THE REGIONAL SETTING

The Midlands of Tasmania comprise the long-settled belt of plains along the line of the Midlands Highway between Bridgewater and Perth (Fig. 1). Westwards, the Midlands are bounded by the scarp of the Central Plateau; to the east the region merges into the Eastern Tiers, low, much dissected plateaus inland of the east coast (see Map 5 in Davies 1965).

In cross-section (Fig. 2), the Midlands present a stepped appearance, interpreted as a sequence of relict erosion surfaces developed across Permian and Triassic sediments extensively penetrated by Jurassic dolerites (Davies 1959, 1967). A major erosion surface between 90 — 275 m above sea level is represented by the plains north of Tunbridge (the only extensive inland plains in Tasmania) and those around Kempton to the south. Lake Tiberias (42°22'S, 147°22'E, 442 m) occurs on the next higher erosion surface, the central Midlands. Dolerite-capped residuals of a yet higher surface (represented by the plains around Interlaken on the Central Plateau) are common on the central Midlands.

Aeolian sand sheets and lunette dunes of probable late last glacial age (Sigleo & Colhoun 1975) are widespread in the Midlands. Pleistocene solifluction deposits mantle the slopes of ridges down to 400 m: the high plateaus of Ben Lomond and the Central Plateau supported small icecaps (Derbyshire *et al.* 1965, Davies 1967).

Due to the pronounced west-east gradient in precipitation across Tasmania, the Midlands lie wholly within the rainshadow zone of the Central Plateau. In contrast to humid and perhumid climates over much of the island, the Midlands are subhumid (Gentilli 1972). Annual precipitation totals are everywhere less than 750 mm and do not significantly vary with elevation (see Nicholls & Aves 1961). Much of the precipitation is derived from infrequent incursions of moist air masses from the Tasman Sea, giving the Midlands one of the least reliable rainfalls in Tasmania (Scott 1956, Langford 1965). Variation in the strength of the prevailing westerly air stream is significant: the Midlands are driest when the westerlies are strongest (July — September) or, alternatively, absent (January — March, when evapo-transpiration losses exceed rainfall gains) (Bur. Met. 1975). Snow falls are rare.

Thermal regimes in the Midlands show a slight continental effect. Despite a mild annual mean temperature of 10°C at Oatlands (432 m), extremes recorded here (Max. 40°C, Min. −12.8°C) are greater than those at Miena (1,013 m) on the

*Botany Department, University of Tasmania. Box 252C, G.P.O., Hobart, Tasmania 7001.

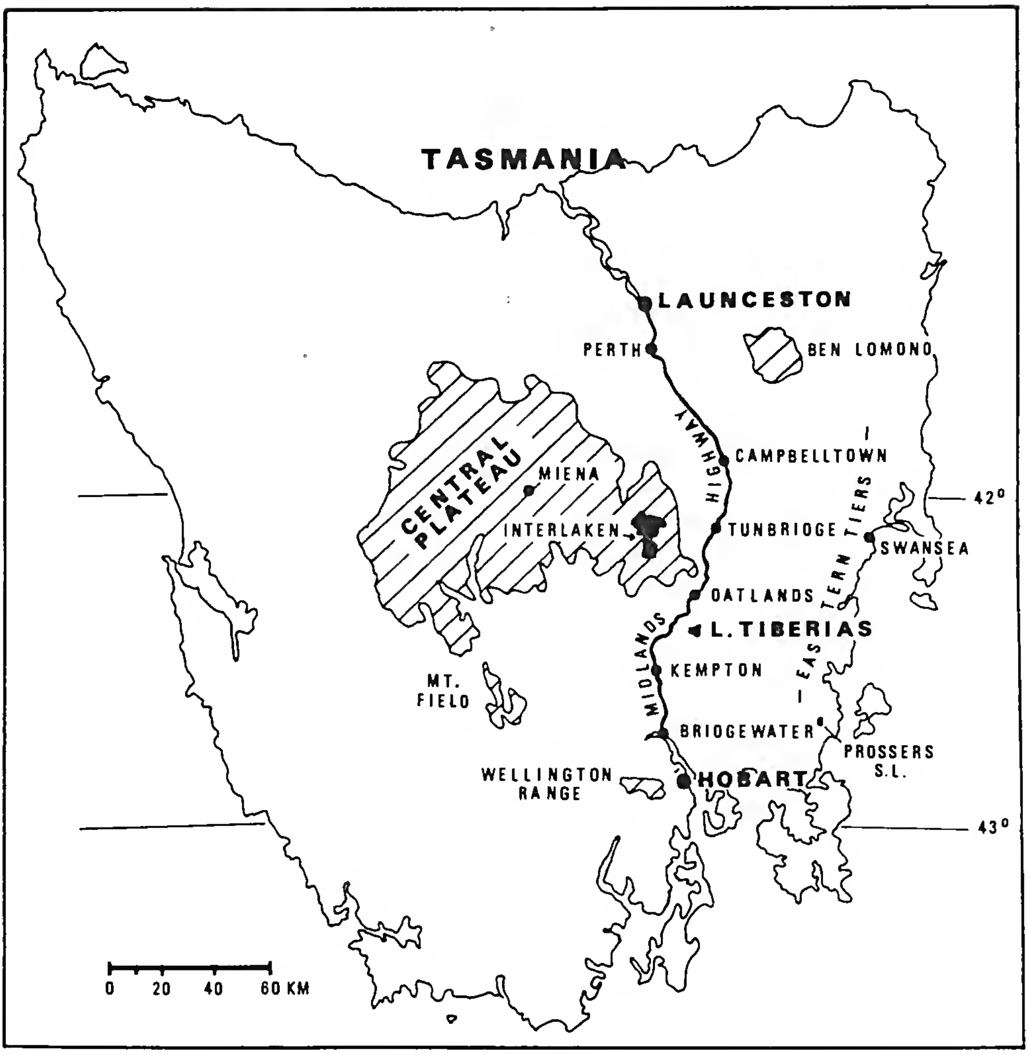

FIG. 1 — Location of Lake Tiberias.

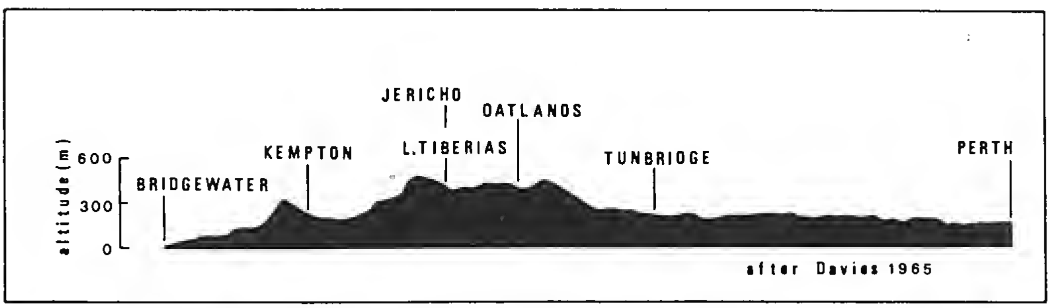

FIG. 2 — Profile along the Midlands Highway.

Central Plateau and there is no frost-free month (Foley 1945, Bur. Met. 1956).

The presence of saline lakes (Nye 1921, Buckney & Tyler 1972), free carbonates in sub-surface soil horizons (Cowie 1959, Leamy 1961) and open vegetation types (Jackson 1965, 1973) in the Midlands reflects the low effective rainfall.

The characteristics of soils developed are essentially correlated with the lithology of the parent material:

Triassic Sandstones, by far the most common sedimentary rock in the central Midlands, carry stony and infertile podzolic soils, podzols or shallow brown earths. Soils on siliceous strata are better-draining but less fertile than those on feldspathic and micaceous strata.

Permian Mudstones carry very infertile and shallow podzolic soils. These are liable to both rapid desiccation and waterlogging.

Dolerite, usually outcropping on ridge slopes and tops, carries podzolic soils of shallow, stony silt loams over plastic clay horizons. At low elevations, brown earths have developed. All dolerite soils are more fertile than those on sedimentary strata but are prone to waterlogging and rapid desiccation. Heavy textured black earths have developed on the more recent alluvium. Windblown sediments carry brown earths.

In contrast to the forested plateaus on either side, vegetation in the Midlands is characteristically savannah woodland on the interfluve ridge niche extending into tussock grassland in the broad shallow valley niche. Few, if any, plant communities have escaped firing or grazing pressures associated with Aboriginal and European occupation of the region. The former may extend back some 18,000 years (Bowdler 1974, Sigleo & Colhoun 1975). Although 'fire-stick farming' (Jones 1969) has probably maintained in the long-term the extensive Midlands grasslands, it is unlikely that present-day climates would support a vegetation type more closed in structure or mesic than *Eucalyptus* dry sclerophyll and woodland in the Midlands.

Organic lake deposits occurring in the Midlands are rarely more than 1 metre-deep black clays, impenetrable to hand-coring techniques. The presence of sedge peats 3 metres deep in Lake Tiberias therefore is an exceptional opportunity to explore the more recent past vegetation and climate of the central Midlands by pollen analysis.

THE STUDY SITE

Lake Tiberias (Pl. 28) occupies a shallow valley in Triassic sandstones at the head of the Jordan River, 10 km south of Oatlands. To the east, the next lower erosion surface, represented by the 180 m deep valley of the Coal River, comes within 0.8 km of the Lake; 100–250 m high dolerite ridges occur around the lake catchment area.

The lake basin is roughly triangular, *c.* 10 km^2 in area within a catchment area of *c.* 21 km^2. Lunette dunes occur along the southeastern shore, suggesting seasonal desiccation and deflation of the lake basin during the Pleistocene (see Bowler 1973). Minor streams, dry during summer, enter the lake at the northeast and southwest corners. Outflow is across a dolerite rock bar at the northwest end. Before the construction of a small, ineffectual weir across the outflow, the surface of the peat infill was probably close to the level at which water drained from the lake. At present the lake is hydrologically open only during winter. Consequently, the water is subsaline (R. T. Buckney, pers. comm.)

Meteorologic conditions at the lake would be similar to those at Oatlands (Table 1): overall cool, with a mean daily temperature above 10.5°C from October to March inclusive and an annual rainfall of 510 mm distributed (by Tasmanian standards) uniformly throughout the year.

Soils (Hubble 1946) and plant communities at Lake Tiberias follow the pattern common to the

TABLE 1

DISTRIBUTION OF RAINFALL AND EVAPORATION AT OATLANDS
(mm of rain)

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*Jul.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Yr.*
Precipitation, 1882-1964	42.9	41.1	40.1	50.0	56.0	54.1	43.2	43.9	41.9	57.7	48.8	57.4	567
Evaporation (est.)	130	100	75	50	40	25	25	25	40	50	75	100	710
No. rain days	9	9	10	13	15	16	17	17	14	15	14	12	161

After Bur. Met. (1966), J.E.S. Townrow (pers. comm.).

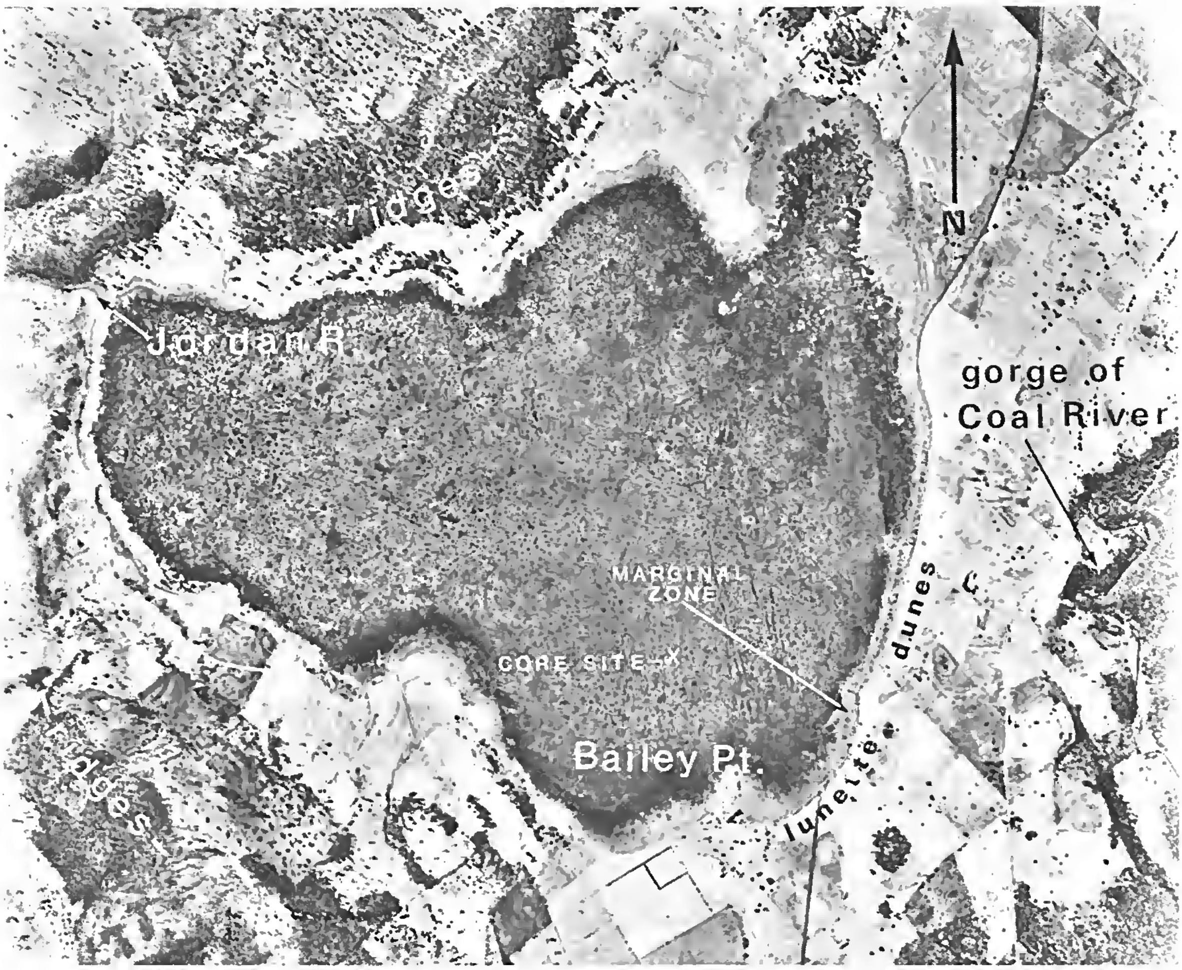

PLATE 28
Aerial photograph of Lake Tiberias.

Midlands. Consequently, dry sclerophyll forest occurs within 200 m, and isolated eucalypts adjacent to the lake. An estimated 20% of the catchment basin supports *Eucalyptus*-dominated formations (cf. Nye 1922). Plant names and authorities follow Curtis (1956-67) and Willis (1970).

Where uncleared (Pl. 28), the slopes of surrounding ridges support open-forest, low open-forest and woodland of *Eucalyptus ovata — E. pauciflora, E. viminalis — E. amygdalina* and *E. pauciflora — E. rubida* intermixed with small trees of *Exocarpos cupressiformis, Acacia dealbata, Banksia marginata, Dodonaea viscosa, Bursaria spinosa* and, on the driest sites, *Casuarina stricta.* Grasses are common as a ground cover. This contrasts with the predominantly xerophytic shrub understory (species of Epacridaceae, Proteaceae, Myrtaceae, Compositae, Papilionaceae and Mimosaceae) found in protected sites and in extensive *Eucalyptus* open-forests peripheral to the Midlands (see Map 7 in Jackson 1965). Isolated trees extend into the valley grasslands. Where unimproved, these grasslands are dominated by *Poa poiformis. Themeda australis* and *Lomandra longifolia* may be dominant on clayey soils. Grazing is the main form of land usage with small areas sown for fodder crops (Scott 1965). Besides introduced grasses, the exotic species *Ulex europeus, Taraxacum officinale, Plantago lanceolata* and *Trifolium* are common in the pastures.

Mesophytes are uniformly remote from Lake Tiberias. Wet sclerophyll species such as *Pomaderris apetala* and *Dicksonia antarctica* occur in damp gullies near the east coast and on the scarp of the Central Plateau to the north. The nearest stands of *Nothofagus cunninghamii* cool temperate

rainforest and probably the light-demanding rainforest conifer *Phyllocladus aspleniifolius* occur 50 km to the south and southeast, on the Mt. Wellington Range and Prossers Sugar Loaf, but extensive rainforest (with *Phyllocladus* and *Dicksonia*) and alpine species such as *Nothofagus gunnii, Microstrobos* and *Podocarpus* are much more distant, on and west of Mt. Field and the northern rim of the Central Plateau.

With the exception of a marginal zone some 60 m wide (used as a water meadow), Lake Tiberias is covered by the one sedge species, *Lepidosperma longitudinale*. The structure of this sedgeland varies with the micro-relief of peat surface and the extent of disturbance by cattle: hummocky near the edge and sparse but continuous towards the centre. A coprophilous association of *Epilobium* and unidentified species of Solanaceae, Compositae and Gramineae occurs around those hummocks used by birds as nesting sites. Otherwise *Utricularia dichotoma* is usually the only other species to occur with the sedge dominant. In contrast, the marginal zone supports an exceedingly dense and diverse community of free-floating and rooted aquatics, including *Triglochin procerum, Myriophyllum propinquum, Villarsia exaltata, Scirpus fluitans* and species of *Potamogeton, Lemna* and Gramineae. Eutrophication effects are apparent and floristic dominance varies from year to year.

Water depths may exceed 1.5 m during winter. Water table levels tend to remain above the lake bed of organic muds in the marginal zone but elsewhere the lake dries out to form a mosaic of shallow pools and sedge 'islands' across the peat infill during summer.

Lake sediments were cored using a Hiller corer at a site *c.* 400 m north of Bailey Point (Pl. 28). These comprise 215 cm of well humified sedge peats overlying an unknown depth of lacustrine clays. An algal gyttja containing numerous shells of the freshwater gastropod *Potamopyrgus* (B. J. Smith pers. comm.) occurs at the junction. Depths measured from the surface of the rhizome mat are:

0 – 15 cm:	sedge bases, coarse fibrous peat
15 – 215 cm:	dark brown well humified to slightly fibrous peat
215 – 220 cm:	grey-green algal gyttja with gastropod shells
220 – 250 cm:	grey-brown clay
250 – 283 cm:	blue-grey clay

A gastropod shell horizon intercalated between the peat and clays was recorded at similar depths in two additional cores taken between this site and Bailey Point. Peats immediately overlying the gastropod horizon in another core taken by A. Goede (Geography Dept., University of Tasmania) prior to this study are dated at 9,550 ± 200 ^{14}C yr B.P. (GaK-2239), (Goede unpubl.). The apparently level nature of the off shore lake floor beneath the peat and similarities in stratigraphy make it likely that Goede's date is applicable to level *c.* 215 cm in this study.

PREPARATION OF THE POLLEN DIAGRAM

The core was sampled at 8 cm intervals in the field and the sealed samples returned to the laboratory. These were wet sieved, treated with cold hydrofluoric acid if clay-rich, and then with hydrolysis and acetolysis following the methods outlined by Faegri and Iversen (1964) and Franks (1965). Pollen and spores were counted at X 200 magnification and, when necessary, identifications checked at higher magnifications against a virtually complete pollen herbarium of the native Tasmanian flora prepared by M.K. Macphail. Whole mounts were counted to avoid under-coverslip sorting effects.

The pollen diagram (Fig. 3) is based on a pollen sum comprising the modern regional pollen rain in Tasmania, Gramineae, *Phyllocladus*, Chenopodiaceae-Amaranthaceae (listed as Chenopodiaceae in Fig. 3), *Casuarina, Pomaderris apetala*-type, *Dicksonia, Nothofagus cunninghamii, Eucalyptus* and Compositae in approximate order of decreasing representation, and other types known to be widely dispersed, *Dacrydium, Dodonaea, Bursaria, Acacia, Amperea* and *Pomaderris elliptica* (Macphail 1975, 1976). All pollen and spores from coastal, rainforest and highland species are long distance transported with respect to Lake Tiberias. *Nothofagus gunnii, Microstrobos* and *Podocarpus* are omitted from the pollen sum in order to bring the pollen sum into conformity with pollen sequences from montane Tasmania.

The pollen diagram has been subdivided by eye into local pollen zones defined by variations in the pollen curves of regional pollen producers.

Zone LT-1 (250 cm). The zone, comprising, one pollen spectrum (sample 32), is distinguished by high values for both Gramineae and Chenopodiaceae-Amaranthaceae, and an unidentified stephanoporate type, possibly aberrations of *Myriophyllum* or Chenopodiaceae-Amaranthaceae pollen. Otherwise *Phyllocladus* and *Eucalyptus* overwhelmingly dominate the dry land pollen component and *Myriophyllum* the hydrophyte pollen component.

Zone LT-2 (250-210 cm). Transitional zone with increasing pollen taxon diversity. The base is

defined by a great increase in *Phyllocladus* and, to a lesser degree, *Eucalyptus* at the expense of Gramineae and Chenopodiaceae-Amaranthaceae. Thereafter, *Phyllocladus* values (and those of the stephanoporate type) decrease over the zone whilst *Eucalyptus* rises to make up 60% of the pollen sum. Equally diagnostic of the zone are maximum values for *Dicksonia*, Compositae, the herb *Oreomyrrhis* and fern spores. Patterns in the hydrophyte component are similar: *Myriophyllum* rises greatly in abundance at the base and remains very common throughout; *Cladium-Lepidosperma* is initially common but thereafter decreases whilst *Triglochin* increases across the zone.

Zone LT-3 (210-0 cm). Eucalyptus makes up 70-80% of the pollen sum. Values for rainforest taxa and Chenopodiaceae-Amaranthaceae are low to negligible throughout, with no discernible trends of any significance. A pollen type conforming to that of *Pomaderris apetala* but possibly including some variants of *Spyridium* rises abruptly in value to 16% at 184 cm then decreases in irregular fashion to 2-4% over the zone. Conversely, *Casuarina* and Gramineae increase to 10% of the pollen sum in the upper third of the zone. Fluctuations in the hydrophyte component are more marked. The zone is informally subdivided according to changes in the relative proportions of sedge and aquatic pollen types:

(i) High percentages of *Myriophyllum*, sporadically high values for *Triglochin, Cladium-Lepidosperma* and Restionaceae and increasing representation of the sedge pollen taxon *Heleocharis-Scirpus.*

(ii) Initially high and thereafter decreasing values of *Heleocharis-Lepidosperma* with negligible values of *Myriophyllum* and *Cladium-Lepidosperma.*

(iii) Low to moderate percentages of *Cladium-Lepidosperma* with negligible values of *Heleocharis-Scirpus, Myriophyllum* and *Triglochin.*

INTERPRETATION OF THE POLLEN DIAGRAM

Interpretation of the pollen diagram (Fig. 3) relies heavily on the present-day distribution of the source plants across Tasmania (see Appendix) but is supported by a study of the modern pollen rain across Tasmania (Macphail 1976). Negligible amounts of pollen from the marginal zone aquatics in the surface sample suggest that the sedge cover greatly restricts the movement of pollen within the lake basin. Hence the dispersal of dry land pollen types into off-shore areas is by atmospheric rather than by water transport processes. The hydrophite pollen component is unlikely to represent more than vegetation at the core site: sporadic occurrences of pollen and spores from severely under-represented species, including most sclerophyll understory shrubs (Macphail 1975) are of little significance.

Conversely, pollen from any regional pollen producer likely to have always been remote from Lake Tiberias serves as a measure of the abundance and or proximity of other strong pollen sources likely to grow closer to the lake. In this analysis, *Phyllocladus* is such an indicator. The conifer is now restricted to wetter-humid and perhumid situations and, pollen-wise, local stands can be identified by high values of *Pomaderris apetala, Dicksonia* or *Nothofagus cunninghamii.* Whilst there is evidence (Macphail 1976) that *Phyllocladus* formed a now non-extant association with *Eucalyptus* in the early postglacial under climates drier than at present, there is none to suggest *Phyllocladus* could tolerate subhumid conditions, however fertile or fire-free the site.

The pollen diagram illustrates concurrently (i) the development of a freshwater lake colonized by aquatic taxa, then sedges and (il) the replacement of a sparse grassland association by open *Eucalyptus* formations.

LT-1: Sparse Grassland Associations

The appearance of *Myriophyllum* at 251 cm, above sediments virtually devoid of pollen and spores, suggests zone LT-1 reflects the flora of the Midlands at the end of a period in which Lake Tiberias was seasonally or perennially dry. High pollen values for *Phyllocladus* and *Eucalyptus* in this zone and the early part of LT-2 imply these assemblages (from clays sparse in dry land pollen) are the time stratigraphic equivalents of, and have the same sources as, assemblages recording the development of *Phyllocladus-Eucalyptus* formations on mountains in western and southern Tasmania between 11,000 — 10,000 ^{14}C yr B. P. (Macphail 1976) i.e., zones LT-1 and early LT-2 are late Pleistocene.

Values for other dry land pollen types agree with a distant point of origin for much of the pollen and spores in zone LT-1. *Casuarina* percentages are similar to values reflecting long distance transport elsewhere in Tasmania. Assuming the stephanoporate pollen type is not Chenopodiaceae or Amaranthaceae, values for Chenopodiaceae-Amaranthaceae are below that in a surface sample from within a chenopod community (Hope 1969) but approach values recored in pollen traps in western Tasmania during the island-wide absence

LAKE TIBERIAS. MIDLANDS, TASMANIA.

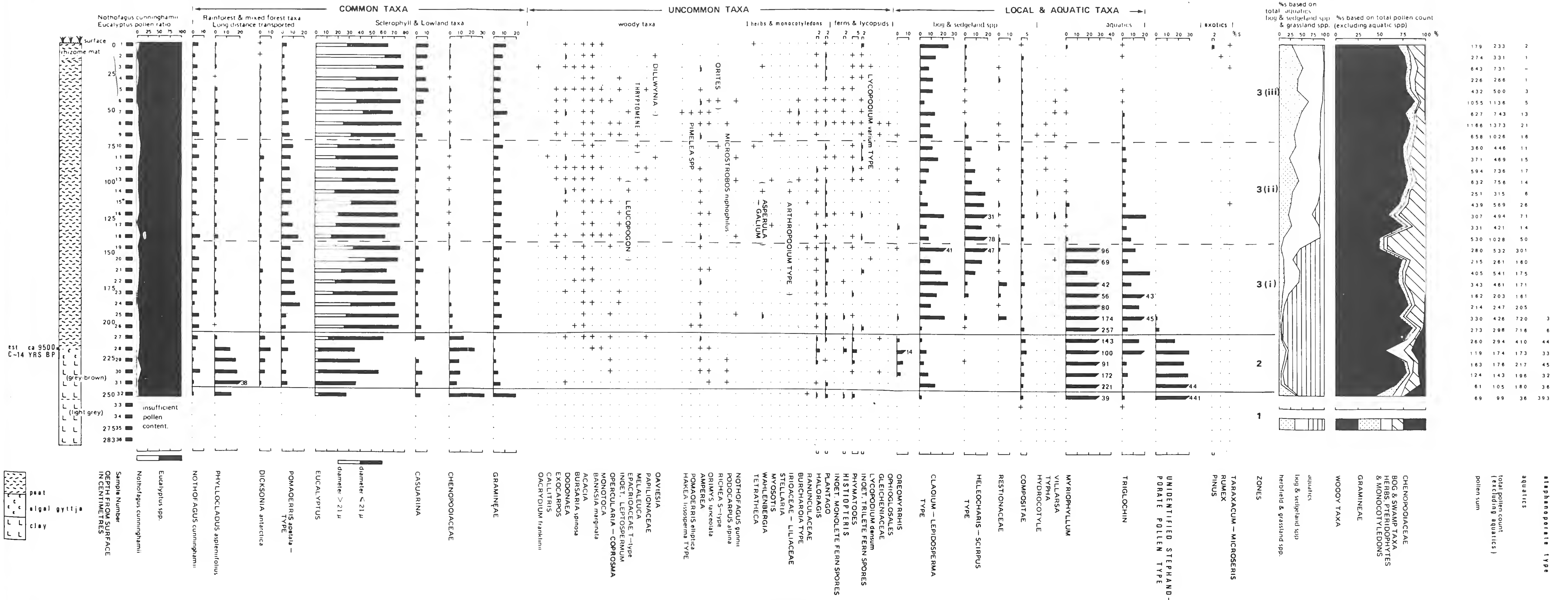

FIG. 3 — Pollen Diagram.
The frequencies of occurrence of all pollen and spores are shown as percentages of the total arboreal pollen plus Gramineae, and long distance transported pollen, of the appropriate sample. (%s less than 1 recorded as +).

of flowering in winter. Accordingly, at least part of the chenopod pollen count may have been derived from mainland communities (cf. Martin 1973). *Eucalyptus* values are accentuated by the pollen sum used and, in any case, are well below the surface sample value. Gramineae values are below those representing local grasslands but are also below values reflecting long distance transport during the late Pleistocene in Tasmania (Table 1 in Macphail 1975).

Therefore, late Pleistocene vegetation in the Central Midlands is likely to have been sparse, most probably very open grasslands lacking trees. Since vegetation on the erosion surface adjacent to but 180 m below Lake Tiberias probably contributed significant amounts of pollen to the local pollen rain, late Pleistocene vegetation on this surface may also have been sparse (cf. Sigleo & Colhoun 1975).

Pollen from *Oreomyrrhis* in zone LT-2 is evidence for markedly colder conditions in the Midlands before *c.* 9,500 ^{14}C yr B. P. (Appendix). Since Lake Tiberias was close to, if not above, the lower limits of late Pleistocene periglacial activity (Davies 1967, Chick & Colhoun 1972), an absence of trees on the higher Midlands in the late Pleistocene is not surprising, whatever the precipitation regime. The inferred sparsity of grasses is however less likely to result from low temperatures. A more probable cause is precipitation values rather lower than the present-day subhumid conditions.

Zone LT-1 therefore indicates that late Pleistocene climates in the Midlands were colder and drier than at present. These conditions are consistent with a late Pleistocene age for aeolian landforms in inland eastern Tasmania and support Flint's hypothesis of accentuated precipitation shadowing effects during glacial periods (Flint 1957 p.432). The modern relationship between dry conditions in eastern Tasmania and strength of the prevailing surface westerly airstream suggests glacial age aridity in Tasmania may well have been associated with increased vigour of the zonal circulation relative to the present (see also Derbyshire 1971, Wilson & Hendy 1971).

The possibility remains that zone LT-1 reflects a chenopod 'cold steppe' community in the Midlands, analogous to the Gramineae-Chenopodiaceae associations of (hot) semi-arid to arid regions of mainland Australia. Gramineae-Chenopodiaceae associations are now rare in inland Tasmania (Appendix in Macphail 1975) and the demise of such a chenopod steppe would be in accordance with the onset of more equable climates across Tasmania during the Holocene.

LT-2: Expansion of *Eucalyptus*

Trends in the pollen curves of wet forest species in zone LT-2 are consistent with, and the pollen and spores probably derived from *Nothofagus cunninghamii* rainforest and *Eucalyptus* wet sclerophyll replacing *Phyllocladus-Eucalyptus* communities on mountains to the west and south of Lake Tiberias between 10,500 — 9,500 ^{14}C yr B. P. (Macphail 1976). Chenopodiaceae-Amaranthaceae pollen values are in agreement with a distant point of origin for much of the dry land pollen and spores in the zone. Despite low Gramineae pollen values, vegetation in the higher Midlands probably remained sparse grasslands. Increasing values for *Eucalyptus* pollen in zone LT-2 are therefore likely to reflect an expansion of eucalypt formations at lower elevations in eastern Tasmania before 9,500 ^{14}C yr B. P.

Since *Eucalyptus* and rainforest trees were well established at elevations higher than but west and south of the central Midlands by 10,000 ^{14}C yr B. P., the difference in time of development (and floristics) of postglacial forests suggests progressive amelioration in climate along a gradient approximating to the modern west-east precipitation gradient. Accordingly, climates in the Midlands during zone LT-2 are likely to have been less severe than for zone LT-1 but still cold and dry relative to the present.

The presence of local *Myriophyllum* then *Triglochin* suggests lake levels remained constantly above the lake floor at the core site during zone LT-2. *Potamopyrgus* shells show that freshwater conditions were present by 9,500 ^{14}C yr B.P.

LT-3: Local Dry Sclerophyll Forest and Savannah Woodland

High values for *Eucalyptus* pollen throughout zone LT-3 (similar to the surface sample value) indicate eucalypts became common on the higher Midlands shortly after 9,500 ^{14}C yr B.P., probably as effective precipitation, and possibly temperatures, reached values close to those of the present-day. A marked rise in the proportion of *Eucalyptus* pollen with diameters greater than 21μ occurs across the zone LT-2/LT-3 boundary. This is consistent with an expansion of warmth-requiring eucalypts since now only those species characteristic of the upper subalpine zone — on dolerite, *Eucalyptus coccifera, E. subcrenulata* and *E. vernicosa* — have pollen always smaller than 21μ diameter. However, the change in pollen size

classes also coincides with the initial phases of peat accumulation. Hence altered pollen extraction procedures (the treatment of clay but not peat samples with HF) might equally well be the explanation.

Other dry land pollen types maintain values across zone LT-3 that are similar to values in the surface sample, e.g. *Nothofagus cunninghamii, Dicksonia, Phyllocladus*, Chenopodiaceae-Amaranthaceae and, within broader limits, Gramineae. This suggests the central Midlands has supported a mosaic of *Poa* grassland with *Eucalyptus* dry sclerophyll forest and woodland since the early Holocene. As it is also probable that the Midlands supported Aboriginal populations during this period, the stability in vegetation may be as much due to a constant fire pressure as to climates remaining subhumid throughout. Minute carbonized particles were present in all peat samples but never in significant concentrations. However fluctuations in the *Eucalyptus* pollen curve, e.g. at the sub-zone 3i/3ii interface, may reflect the variable impact of local fires.

At present fire is a major influence in the Tasmanian environment (Jackson 1968). This emphasizes the need for caution when interpreting palaeo-ecologic evidence from long-inhabited regions. However, given the strong probability that man has been overwhelmingly responsible for past and present wildfires in Tasmania and that fire frequencies about centres of Aboriginal occupation were as high as the prevailing climate permitted (see Jackson 1968, Jones 1968, 1971), then the 'ecologic drift' in plant communities will again provide a relative measure of climatic trends even though meteorologic values are obscured in absolute terms.

One such indicator is the understory flora in *Eucalyptus* forests. Here, of the species which effectively disperse abundant pollen or spores, *Pomaderris apetala* and *Dicksonia* point to a moist forest environment and *Casuarina* and *Dodonaea* to a dry forest environment. Maximum values in zone LT-3 of the respective pollen and spore types suggest the substratum vegetation being represented was distant rather than local, possibly that of forests on the Central Plateau scarp and the Eastern Tiers.

On this basis, the irregularly high values for *Pomaderris apetala*-type pollen in sub-zone 3i and 3ii imply wet sclerophyll forest was then more abundant or located closer to Lake Tiberias within the pollen source area than at present. Assuming relatively constant rates of peat accumulation during zone LT-3, this in turn suggests that effective precipitation in the Midlands during the early to mid-Holocene was above modern values but still inadequate for a general expansion of *Dicksonia* within the same moist forest niche.

Low values of *Pomaderris apetala*-type pollen in subzone 3iii correspond to increasing percentages of *Casuarina, Dodonaea* and Gramineae pollen, suggesting that sclerophyll forests within the pollen source area have become increasingly dry and open-structured since the mid-Holocene. Since *Casuarina* is more fire-sensitive than *Eucalyptus*, an increase in fire frequency alone seems insufficient to account for the expansion of *Casuarina*. Accordingly it is suggested that the postulated wetter phase was followed by less equable conditions leading to the present-day subhumid climate in the Midlands. Less frequent incursions of moist air masses from the Tasman Sea or a shift in the orientation of the Central Plateau rainshadow effect could increase the water deficit period in the Midlands.

At the time of European settlement, Aboriginal population densities are calculated to have been amongst the highest known for 'hunter — gatherer' economies (Jones 1971), presumably due to expanding numbers during the Holocene. An alternative hypothesis, that the increasingly dry, open vegetation of the Midlands was due to an expansion in Aboriginal numbers, is considered less likely since montane rainforest in western and southern Tasmania (areas rather more remote from population centres) changed towards drier *Eucalyptus* dominated formations over approximately the same period (Macphail 1976).

The pollen data are inadequate to determine trends in temperature in zone LT-3.

Hydroseral developments at the core site in zone LT-3 are more clearly defined but less easily interpreted than the dry land vegetation. The stratigraphy demonstrates that this *in situ* vegetation has been a sedgeland since the early Holocene. For much of this period, the sedge dominant has probably been *Lepidosperma*. The temporary rise to dominance of the sedge community corresponding to the *Heleocharis-Scirpus* pollen type in the mid-Holocene was followed by the re-establishment of the '*Lepidosperma*' association. This reversion is likely to reflect changing water levels rather than a natural seral progression, hence a change in effective precipitation.

The marked decline in pollen from the open water aquatics, *Myriophyllum* and *Triglochin*, across the sub-zone 3i/3ii boundary suggests that (locally) sustained high water levels were replaced by alternating drying out and flooding of the peat

surface at some time during the mid-Holocene, presumably as the rhizome mat reached the mean summer level of the water table. Any trend towards lower effective precipitation would compound this change in local hydrology. However it is clear from the pollen record that desiccation of the lake has not been sufficiently prolonged to allow the establishment of woody shrubs at the core site.

CONCLUSIONS

Pollen assemblages preserved in Lake Tiberias do not support the drier mid-Holocene episode postulated for eastern Tasmania between *c.* 7,000 — 3,000 B.P. by Davies (1974). Rather the model proposed here for late Pleistocene and Holocene climates in the Midlands is consistent with those established for montane regions in the southern half of Tasmania (Macphail 1976): markedly colder, drier conditions in the late Pleistocene, a rapid amelioration in temperature and precipitation between *c.* 11,000 — 9,000 B.P. leading to an early to mid-Holocene 'optimum' in which climates were wetter (and then possibly warmer) than at present and subsequently, a reversion towards less equable conditions leading to the modern climate. Recent phases of valley alluviation and aeolian deposition in southeastern Tasmania may well reflect the geomorphic impact of Aboriginal fires during short-term periods of severe climate (see also Goede 1965).

Revision and extension of this model of climatic change will require much additional pollen data well supported by radiocarbon dates. Cleveland Lagoon 15 km north of Campbell Town may prove suitable for palaeo-ecologic research. Pollen analysis of the Pleistocene clays infilling Lake Tiberias and many other of the Midlands 'lagoons' may extend the history of the region into earlier Quaternary times.

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APPENDIX

Source Plants for Pollen in Tasmania

Climates in Tasmania range from cool, perhumid on the west coast to warm, subhumid on the east coast. Plant communities are broadly zoned along this precipitation gradient and upslope on mountains with (increasing) precipitation and (decreasing) temperature. The climatic timberline varies in altitude from 750-915 m in the southwest and west to 1,220 m in the northeast and east. Subalpine climates extend some 300 m below the timberline.

The wide range of microclimates created by the island-wide mountainous terrain blurs boundaries between plant formations. Much of the vegetation is fire-disturbed. As a result, many sclerophyll species characteristic of drier eastern climates are widespread in perhumid environments in the far south, southwest, west and northwest, regions climatically capable of supporting *Nothofagus cunninghamii* cool temperate rainforest from sea level to the timberline: species characteristic of wet sclerophyll forest are common within disturbed rainforest.

Soils in eastern Tasmania are developed on relatively fertile Mesozoic sediments and dolerite; those in western Tasmania are developed on highly infertile Precambrian metamorphic rocks. Soil impoverishment associated with repeated fires helps maintain open-structured sclerophyll and sedge communities in the closed-forest niche.

Pollen Taxon	Family	Plant Habit	Known Ecology and Distribution
Acacia	Mimosaceae	Shrubs & trees	Mainly in coastal heath, drier sclerophyll forests and (*A. melanoxylon*, *A. verticillata*) along wet gullies and river banks. *A.dealbata* is common in wet forests disturbed by fire.
Amperea	Euphorbiaceae	Low shrubs	In heath and (western Tasmania) on poor soils.
Arthropodium	Liliaceae	Herbs	Locally common in open areas in eastern Tasmania.
Asperula-Galium	Rubiaceae	Herbs	Mainly in drier open situations up to 1,220 m.
Banksia marginata	Proteaceae	Shrubs & under-canopy trees	Widespread in coastal communities, drier sclerophyll forest and subalpine woodland up to 1,067 m.
Beyeria	Euphorbiaceae	Shrubs	Common on gully sides in eastern Tasmania.
Burchardia	Liliaceae	Herbs	Open situations in northeast.
Bursaria spinosa	Pittosporaceae	Small trees	Common in open woodlands and dry sclerophyll forest in eastern Tasmania.
Callitris	Cupressaceae	Small trees	Local on east coast and near Launceston.
Casuarina	Casuarinaceae	Shrubs & under-canopy trees	Widespread in coastal communities and on very dry hillsides inland in eastern Tasmania. *C. monilifera* is abundant on freely-draining sites in heathland up to *c.* 600 m in western Tasmania.
Chenopodiaceae-Amaranthaceae	Chenopodiaceae & Amaranthaceae	Herbs & shrubs	Rare inland of coast. Not in forests, heath or at higher elevations than the Midlands.
Cladium-Lepidosperma	Cyperaceae	Herbs	Swamps and wetlands at lower elevations.

APPENDIX (Continued)

POLLEN TAXON	FAMILY	PLANT HABIT	KNOWN ECOLOGY AND DISTRIBUTION
Compositae	Compositae (Asteraceae)	Herbs, shrubs & subcanopy trees	Widespread and locally abundant in all communities except undisturbed rainforest.
Dacrydium franklinii	Podocarpaceae	Emergent trees	Local in riparian rainforest and around lakes up to 750 m in far south, southwest, west and northwest.
Daviesia	Papilionaceae	Shrubs	Heaths and open situations in eastern Tasmania.
Dicksonia antarctica	Dicksoniaceae	(Tree fern)	Wet gullies and wetter sclerophyll forests up to *c*. 600m in eastern Tasmania. Rare on infertile soils (much of western Tasmania). Not in undisturbed rainforest.
Dillwynia	Papilionaceae	Low shrubs	Heath and grasslands in eastern Tasmania.
Drimys lanceolata	Winteraceae	Shrubs & small trees	Widespread in wetter forests (not undisturbed rainforest), subalpine and alpine heaths.
Epacridaceae (T-type)	Epacridaceae	Shrubs & small trees	Widespread and abundant in open communities from sea level to mountain summits (1,520 m).
Eucalyptus	Myrtaceae	Canopy trees	Dominants of sclerophyll forests and subalpine woodlands. Common as emergent above regenerating rainforest. Subalpine species may occur as isolated shrubs above the timberline in western Tasmania.
Exocarpos	Santalaceae	Shrubs & parasitic trees	Open-woodland and dry sclerophyll forest. *E. humifusus* is common in subalpine woodland and alpine heath.
Gramineae	Gramineae (Poaceae)	1. Aquatic herbs 2. Dry land herbs	Widespread but occasional in very shallow lakes. Dominant on Midlands plains, cleared lands elsewhere and frost-prone plains on the eastern Central Plateau. Rare within forests and alpine communities.
Gleichenia	Gleicheniaceae	(Fern)	Mainly subalpine and alpine bog communities.
Hakea lissosperma	Proteaceae	Tall shrubs	Subalpine woodlands, reaching sea level in southwest.
Haloragis	Haloragaceae	Herbs	Common in open, usually damp, situations from sea level to mountain summits.
Heleocharis-Scirpus	Cyperaceae	Herbs	Freshwater lakes including high altitude tarns.
Histiopteris	Dennstaedtiaceae	(Fern)	Widespread in wet shady places and burnt wet forests.
Hydrocotyle	Umbelliferae	Herbs	Stream banks and wet places below subalpine zone.

APPENDIX (Continued)

POLLEN TAXON	FAMILY	PLANT HABIT	KNOWN ECOLOGY AND DISTRIBUTION
Iridaceae-Liliaceae	Iridaceae & Liliceae	Herbs	Open situations at all elevations.
Leptospermum	Myrtaceae	Shrubs & trees	Common in heaths at all elevations. *L. lanigerum* is abundant on poorly drained subalpine sites.
Leucopogon	Epacridaceae	Shrubs	Mainly coastal heath, but occurs in subalpine grasslands.
Lycopodium densum	Lycopodiaceae	(Club moss)	In heath at lower elevations.
L. varium	Lycopodiaceae	(Club moss)	On shallow soils in subalpine and alpine zones.
Melaleuca	Myrtaceae	Shrubs	Wet heaths, swamps in northwest and extending on peaty soils to 1,370 m.
Microstrobos niphophilus	Podocarpaceae	Shrubs	Lining streams and lakes between 915 – 1,370 m on mountains of Central Plateau, west and southwest.
Monolete fern spores	—	(Ferns)	Mainly damp shady places. *Blechnum* fernland forms the subcanopy stratum in undisturbed rainforest.
Monotoca	Epacridaceae	Shrubs & small trees	Wet sclerophyll forest, disturbed rainforest and (*M. empetrifolia*) subalpine and alpine heaths.
Myosotis	Boraginaceae	Herbs	Moist situations up to timberline.
Myriophyllum	Haloragaceae	Herbs	From lowland brackish and freshwater swamps to alpine tarns.
Nothofagus cunninghamii	Fagaceae	Canopy trees	Sole dominant in cool temperate rainforest. Species restricted to regions receiving *c.* 1500 mm rainfall p.a. and at least 50 mm per summer month. Common in shrub form in the subalpine/alpine tension zone on all mountains.
N. gunnii	Fagaceae	Deciduous shrub	Local in exposed situations above *c.* 915 m on mountains of Central Plateau, west and southwest.
Opercularia-Coprosma	Rubiaceae	Herbs & shrubs	In sclerophyll communities from sea level to mountain summits. *Coprosma* is common in subalpine woodland and disturbed rainforest.
Oreomyrrhis	Umbelliferae	Herbs	Local in montane grassland and mountain summits. *O.eriopoda* is rare in coastal heath.
Orites	Proteaceae	Shrubs	Abundant in subalpine woodlands and alpine heath.
Papilionaceae	Papilionaceae	Herbs & shrubs	Pastures and drier sclerophyll communities. Not in rainforest. *Pultenaea subumbellata* occurs up to 1,220 m in eastern Tasmania.

APPENDIX (Continued)

POLLEN TAXON	FAMILY	PLANT HABIT	KNOWN ECOLOGY AND DISTRIBUTION
Phyllocladus aspleniifolius	Podocarpaceae	Tree	On margins of undisturbed rainforest, becoming common in disturbed rainforest environment. Extends into logged wet sclerophyll forest and, in shrub form, up to the timberline in open situations.
Phymatodes	Polypodiaceae	(Fern)	Damp shady places.
Pimelea	Thymelaeaceae	Shrubs	Widespread in heaths and forests at all elevations.
Pinus	Pinaceae	Trees	Introduced as windbreak in settled lowlands.
Plantago	Plantaginaceae	Herbs	Widespread on open ground up to mountain summits.
Podocarpus alpina	Podocarpaceae	Low Shrub	Local in exposed situations above *c*. 915 m.
Pomaderris apetala-type	Rhamnaceae	Subcanopy tree	Characteristic of the wet sclerophyll forest ecotone (1140-1520 mm p.a. rainfall). Common in wet gullies in eastern Tasmania and in disturbed rainforest on dolerite soils.
P. elliptica	Rhamnaceae	Shrub	Disturbed open ground and in drier sclerophyl communities up to 450 m in eastern Tasmania
Ranunculaceae	Ranunculaceae	Herbs	Moist to wet situations up to 1,220 m.
Restionaceae	Restionaceae	Herbs	Widespread in heaths and sedgelands at all elevations.
Richea (S-type)	Epacridaceae	Shrubs	Mainly subalpine and alpine heaths. *R. pandanifolia* is common in broken-canopied rainforest stands.
Rumex	Polygonaceae	Herbs	Mainly introduced weeds in pastures and clearings.
Stellaria	Caryophyllaceae	Herbs	From lowland marshes in north to dry stony sites.
Taraxacum-Microseris	Compositae	Herbs	Pastoral weeds.
Tetratheca	Tremendaceae	Low shrubs	Heath and drier sclerophyll forest.
Thryptomene	Myrtaceae	Shrub	Local on east coast.
Triglochin	Juncaginaceae	Herbs	Brackish and freshwater lowland swamps.
Trilete fern spores	—	(Ferns)	Throughout all but driest plant communities.
Typha	Typhaceae	Herb	Ponds and along streams in eastern Tasmania
Villarsia	Gentianaceae	Herb	Swamps and marshes, usually lowland.
Wahlenbergia	Campanulaceae	Herbs	Open grassy situations, extending under drier sclerophyll forests and (*W. saxicola*) onto mountain summits in rocky places.

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NEW SPECIES AND NEW RECORDS OF AUSTRALIAN ATHECATE HYDROIDS

By JEANETTE E. WATSON*

ABSTRACT: Eight species of Australian athecate hydroids from 6 families including 4 new species are described and discussed. Species newly described include *Tubularia exxonia*, *Rosalinda marlina*, *Merona operculata* and *Stylactis betkensis*. *M. operculata* constitutes a new record for the genus from Australian waters and *R. marlina* provides the first record of the genus for the southern hemisphere. The second record of *Stylactis* in Australia is from an estuarine habitat previously unrecorded for the genus. Augmented descriptions, new distributional and ecological data, and extensions of range are given for 4 species, *Zyzzyzus spongicolus*, *Sarsia radiata*, *Turritopsis nutricula* and *Bimeria australis*, already known from Australia. The hydroid and medusa stages of *T. nutricula* and *S. radiata* are also redescribed.

INTRODUCTION

General: The eight species of athecate hydroids described and discussed in this paper include four new species belonging to four genera. Three of these genera have not been recorded before from Australian waters and the fourth has been recorded from Australia only once previously, from Queensland. Three of the remaining four species are endemic to southern Australia but have not been recorded since their original description; the remaining species is cosmopolitan. New geographic and bathymetric records, and ecological data are given for these already known species.

The athecate hydroid fauna of Australia is poorly known, only 38 species, including 20 endemic species, having been recorded to date from the entire 20,000 km of coastline. Some of these records are doubtful, and a few species, such as *Tubularia pygmaea* Lamouroux were so poorly described from inadequate material that it is unlikely the species will ever be recognised again. Most of the species described from Australia are however, not well known, many having been recorded only once, in their original description. Most are recorded from warm temperate and subtropical waters, while only 9 species have so far been recorded along the southern cool temperate coastline below 34°S, from Sydney to Cape Naturaliste in Western Australia. This apparent paucity of species in southern waters, and indeed all around the Australian coastline, seems to be due more to sporadic collecting activity and lack of interest in athecate hydroids over the past century, and in particular to the crudity of collecting methods employed, than to any lack of abundance or diversity of this group in Australian seas.

Among the earliest systematic accounts of athecate hydroids in the Australian literature were those by R. von Lendenfeld (1884) who described a number of medusae and hydroid colonies from Port Jackson, New South Wales. Unfortunately, some of his descriptions are confusing, while others contain inaccuracies which have undoubtedly led to great difficulties in identification of certain species by later workers. W.M. Bale, Australia's most prolific author on the hydroida, described only 4 athecate hydroids, from Port Jackson, and Port Phillip Bay, Victoria, among the total of 127 species he published in the years 1882-1926 (Smith & Watson 1969). Other workers who have described or recorded athecate hydroids at various times from the southern coast are Gray (1868), Spencer (1891), Stechow (1924, 1925), Blackburn (1937, 1942), Ralph (1966), Watson & Utinomi (1971), and Watson (1973).

With the exception of one estuarine and one deep water species, all material on which this paper is based was collected by the author or others, using SCUBA. Collection and observation *in situ*, supported by close-up underwater photography,

*74 Nimmo Street, Essendon, Victoria 3040; Honorary Associate, Invertebrate Zoology, National Museum of Victoria, Russell Street, Melbourne 3000.

now permits a much more detailed account of their morphology in life and their ecology, and provides habitat data upon hydroids formerly impossible to obtain through older methods of collecting. All type material and microslides of figured specimens are lodged in the National Museum of Victoria, Melbourne (NMV).

Zoogeography and Ecology: Three of the four species newly described in this paper belong to genera of rare occurrence and of restricted distribution on a world scale. *Merona* has hitherto been known only from *M. cornucopiae*, a species occurring in widely separated localities in the northern hemisphere, the Shetland Isles, the Mediterranean, the Pacific and Atlantic coasts of North America, the Seychelles, in the tropical Indian Ocean, and from the Agulhas Bank between the Indian and Atlantic Oceans. The range of *Zyzzyzus*, known to date only from *Z. solitarius*, a rare South African species, occurring also in the Cape Verde Islands and Trinidad, is now extended to include temperate and cool temperate Australian seas.

Rosalinda, here recorded for the first time from the southern hemisphere, was formerly known from two species restricted to the Bay of Biscay (*R. williami*), and the North Sea (*R. incrustans*). The new species of *Rosalinda* described here also extends the bathymetric range of the genus from deep water (440 m) upward to shallow depths (10 m), well within the zone of wave action.

Stylactis, with fifteen species, is recorded from the North Atlantic, the Atlantic coast of North and South America, the Mediterranean, Japan, Indo- and Central Pacific regions, the Queensland coast of Australia, and doubtfully from South Africa. Only three species, including the doubtful record from South Africa, are recorded from subequatorial waters of the southern hemisphere. The species of *Stylactis* display a wide bathymetric range, occurring from the littoral, where the genus is most commonly recorded, to the archibenthal zone. The present record is, however, the first of the genus from a brackish water habitat.

Turritopsis nutricula is a well known species of cosmopolitan distribution which has been recorded under three synonyms in Australia. Its presently known distribution is along the southeastern and southern coastline; it has not yet been recorded from tropical Australia.

Bimeria australis and *Sarsia radiata* on present knowledge seem to have a localised distribution in the southeastern corner of Australia, but this may reflect lack of collecting effort rather than a true distributional pattern. For example, *S. radiata*, not recorded since its original description in 1884, now proves to be a common species of seasonal occurrence and it is to be expected that it should be widely distributed through its medusa stage along the southern coastline. Observations on the three previously recorded Australian species (*S. radiata*, *T. nutricula*, *B. australis*) show that all establish hydroid colonies during the southern Australian winter. *S. radiata* liberates medusae during the period of lowest water temperature (11°-13°C), while medusae of *T. nutricula* swarm in coastal and ocean water during the summer months (16°-18°C). In winter, *T. nutricula* and *B. australis* hydroids are particularly abundant, occupying similar habitats in places sheltered from surge with low irradiance. *S. radiata* seems to be capable of occupying habitats where there is mild surge, and since it is tolerant of much higher irradiance levels, it is found in clearer, more oceanic waters. The colonies of *S. radiata*, however, never attain the same luxuriance of growth as shown by that of *T. nutricula* or *B. australis*.

LIST OF SPECIES

	Locality
F. TUBULARIIDAE	
Tubularia exxonia n.sp.	Eastern Bass Strait.
Zyzzyzus spongicolus (von Lendenfeld, 1884)	Port Jackson, New South Wales; Port Phillip Bay, Victoria.
F. CORYNIDAE	
Sarsia radiata von Lendenfeld, 1884	Port Jackson, New South Wales; Port Phillip Bay, Victoria.
F. ZANCLEIDAE	
Rosalinda marlina n.sp.	Eastern Bass Strait.
F. CLAVIDAE	
Merona operculata n.sp.	Westernport Bay, Victoria.
Turritopsis nutricula McCrady, 1856	Port Jackson to Shark Bay, Western Australia.
F. BOUGANVILLIDAE	
Bimeria australis Blackburn, 1937	Southern Queensland to Bass Strait
F. HYDRACTINIIDAE	
Stylactis betkensis n.sp.	Mallacoota, southeastern Victoria.

SYSTEMATIC DESCRIPTION

Family TUBULARIIDAE

Tubularia exxonia n.sp.

(Fig. 1,A,B.)

TYPE MATERIAL AND RECORDS: Holotype, NMV G2800 microslide; NMV G2801 preserved material, remainder of holotype colony, Marlin Oil Platform, eastern Bass Strait, 75 m deep, on sponge; coll. Natural Systems Research Pty. Ltd., 2/9/75.

DESCRIPTION FROM HOLOTYPE: Hydrorhiza a matted reticulum penetrating 5-6 mm into the surface of horny sponge, perisarc of hydrorhiza thick. Stems simple, perisarc thick proximally, becoming thinner distally, reaching a height of 2-3 mm above surface of sponge. Width of stem below hydranth, 0.15-0.25 mm. Hydranth variable in shape, capable of great distension, from globular to spindle shaped. Length of body including oral tentacles (preserved) 0.7-1.0 mm; width 0.3-0.5 mm (hydranth partially distended). Tentacles filiform, 12-14 aboral, 0.75-1.25 mm long and 0.06-0.1 mm wide at base, and 13-15 short oral tentacles 0.25-0.35 mm long; inner surface of aboral tentacles furnished with conspicuous pads of nematocysts (stenoteles, none discharged).

Gonophores cryptomedusoid, borne in tight clusters of 10-12 in various stages of development on a short blastostyle arising between the bases of aboral tentacles. Mature gonophores irregularly elongate, but individual shape variable due to pressure of surrounding gonophores. Length of mature gonophore 0.2 mm.

COLOUR: Body of hydranth and tentacles translucent white, gonophores pink (preserved).

REMARKS: *T. exxonia* does not resemble any other tubularian hydroid known from Australia. The small size of the stem and hydranth and the rather solitary, sparse colonies are characteristics which distinguish it from other known species of *Tubularia*.

The genus *Tubularia* as known at present is represented in Australia by five species. These are *T. ralphii* Bale, 1884, recorded in Port Phillip Bay, *T. pygmaea* Lamouroux, 1816 (described from stems without hydranths and therefore unlikely ever to be recognised again), *T. australis* Stechow, 1924, (= *T. gracilis* von Lendenfeld, 1884) from Port Jackson and Western Australia, *T. larynx* Ellis & Solander, 1768, doubtfully recorded from Port Phillip Bay by Ralph (1966) and from the Great Australian Bight by Watson (1971), and *T. crocea* Agassiz, 1862, doubtfully recorded from Moreton Bay, Queensland by Pennycuik (1959).

It is certain that further intensive collecting using SCUBA will greatly add to the number of species of *Tubularia* known from Australian waters.

Zyzzyzus spongicolus (von Lendenfeld, 1884)

(Fig. 1, C-M)

Tubularia spongicola von Lendenfeld, 1884: 597, pl.26, fig. 50.

Von Lendenfeld (1884) described and figured a hydroid, *Tubularia spongicola*, from Port Jackson, New South Wales. In several respects his description, including relative length of the aboral and oral tentacles, and the 'serrated umbrella margin' of the 'medusostyls', does not agree with his figure. Examination of the preserved type material, and other material of *T. spongicola* held in the Australian Museum, Sydney (Reg. Nos. G10809, G10798) reveals that neither von Lendenfeld's description nor his figure agree with the actual material. The figure of *T. spongicola* shows 24 long aboral and 24 shorter oral tentacles whereas the aboral tentacles in the preserved material number 16. The specimens are too poorly preserved to count the oral tentacles. In his description, von Lendenfeld states that the oral tentacles are about twice as long as the aboral tentacles. He also states that the blastostyles are unbranched, although the type material bears small clusters of gonophores. The gonophores are elongate oval and show no sign of a serrated margin, nor do they resemble the distally flattened cups depicted in his figure. His description of a 'light brown perisarc', and a 'creeping hydrorhiza . . . immersed in horny sponges' is further misleading, since the perisarcal sheath is very delicate and almost transparent. The hydranths are quite clearly solitary and rooted in the sponge by finger-like hydrorhizal processes. It is surprising that von Lendenfeld failed to notice this unique character of the hydrorhiza.

Stechow (1921) erected the genus *Zyzzyzus* (type species *Tubularia solitaria* Warren, 1906) for a hydroid from South Africa without hydrorhiza and liberating actinulae. *Z. solitarius* has since been recorded in the Indian Ocean and Cape Verde Islands (Ritchie 1907), and Trinidad (Millard 1975), as a monospecific genus.

Living material collected from sponges in Port Phillip Bay, Victoria and along the New South Wales coastline by the author is undoubtedly conspecific with von Lendenfeld's species and is referable to *Zyzzyzus*. Although in most respects similar to *Z. solitarius*, the occurrence of both male and female gonophores on the same blastostyle distinguish it from that species.

A redescription of *Z. spongicolus* from living and preserved material is given below.

DIAGNOSIS: Hydranths solitary, rooted in the canal system of the host sponge by finger shaped hydrorhizal processes. Hydrocaulus reaching a height of 5-6 mm of which one third is embedded in the sponge. Hydrocaulus stout, covered by a transversely striated transparent sheath of perisarc terminating in a circular groove below hydranth, the coenosarc of the stem divided into about 12 longitudinal canals connecting with the gastral cavity. Hydranth with 12-16 moderately long aboral tentacles, 0.75-1 mm in length (preserved), and 10-12 shorter oral tentacles. Blastostyles arising just above aboral tentacles, each bearing clusters of up to 6 gonophores in different stages of development, male and female on same blastostyle. Immature gonophores of both sexes oval with slightly raised and flattened distal end, the male retaining this shape to maturity. Female gonophore cryptomedusoid, containing up to 6 eggs of which 2-3

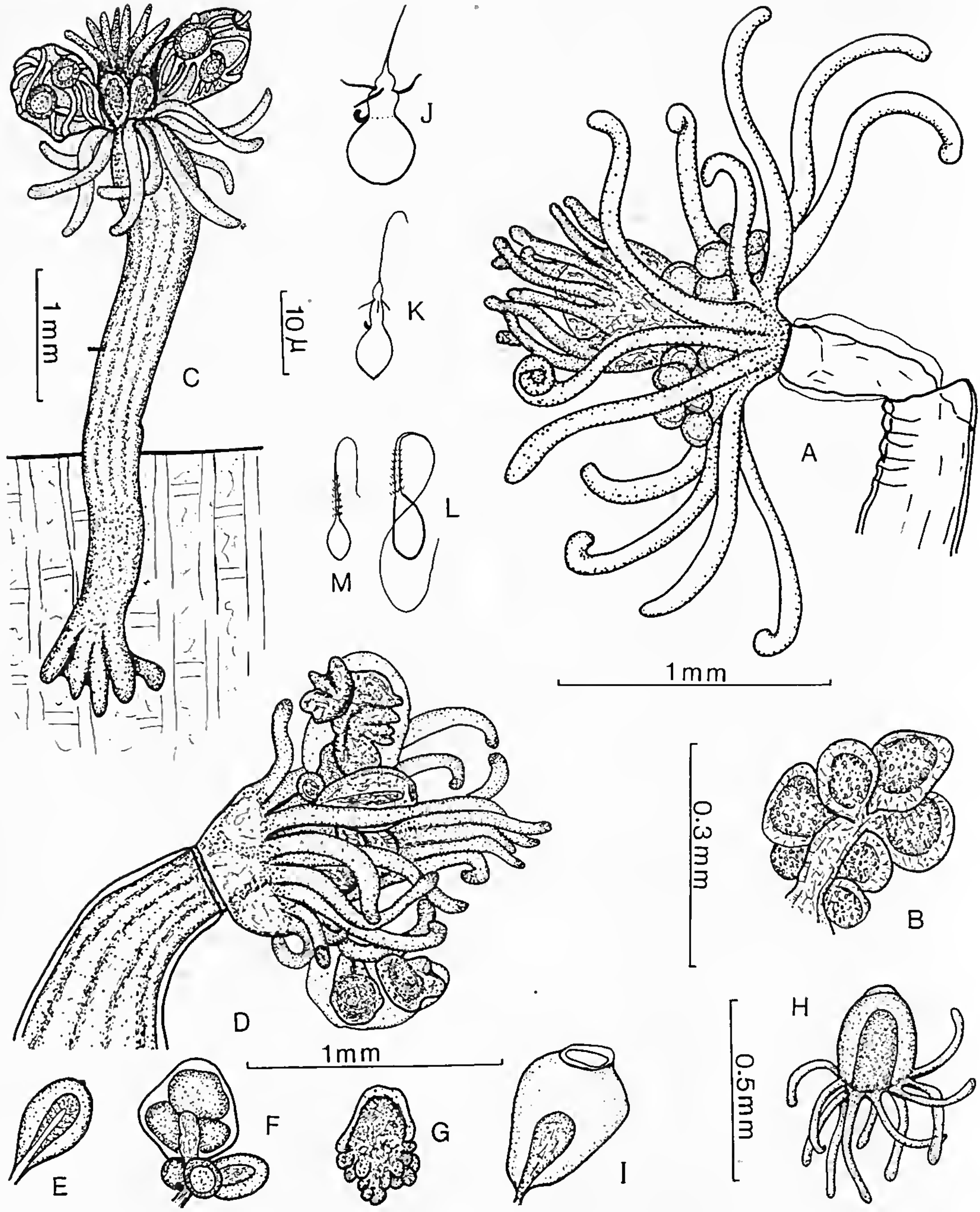

FIG. 1 — *Tubularia exxonia* n.sp. A, hydranth with gonophores; B, cluster of nearly mature gonophores on blastostyle. *Zyzzyzus spongicolus* (von Lendenfeld, 1884). C, fertile hydranth with cut-away section in sponge showing digitate rooting processes; D, detailed view of fertile hydranth with actinulae just prior to liberation; E, male gonophore with sperm cells surrounding spadix; F—I, stages in development of actinula — F, cluster of four gonophores in various stages of development, the largest with three eggs; G, early stage growth with developing tentacle buds (actinula dissected out from gonophore); H, newly liberated actinula, I, empty gonotheca after escape of actinula, spadix still present (D, E, F, I, drawn to same scale); J—M, nematocysts — J, K, stenoteles; L, basitrichous isorhiza; M, heterotrichous anisorhiza.

develop into actinulae *in situ*. Near maturity the female gonophore rapidly enlarges to accommodate the developing actinulae, the outer envelope becoming transparent and irregular in shape, the actinulae clearly visible within. At this stage a circular orifice with raised collar develops at the distal end, and the spadix is pushed to one side. After escape of the actinulae, the spadix remains within the empty gonotheca. At liberation, the actinulae are 0.25-0.3 mm in width across the body with 10-12 long marginal tentacles.

Nematocysts of four kinds are present:

— large stenoteles, very abundant, with spherical capsule, 7.5 – 9 x 9.5μ, butt almost as long as capsule, with 3 large spines.

— smaller stenoteles, also very abundant, capsule a little more elongate, 5.5 x 3μ, butt slender, about two thirds length of capsule.

— basitrichous isorhizas, rare, capsule bean shaped, 8 x 3.5μ, tube long.

— heterotrichous anisorhizas, rare, capsule oval, 3 x 5μ.

COLOUR: Hydrocaulus and tentacles of hydranth translucent white, body of hydranth dull red, gonophores and actinulae at liberation white, spadix of mature female gonophore deep orange.

REMARKS: *Z. spongicolus*, as far as known at present, is associated only with certain species of erect, horny sponges. Although small in size, the hydranths are usually very numerous and thus quite conspicuous on the surface of the sponge. The seasonal range of *Z. spongicolus* is at present unknown but it has been recorded from April to December.

Family CORYNIDAE

Sarsia radiata von Lendenfeld, 1884.

(Fig. 2, A-D)

Sarsia radiata von Lendenfeld, 1884: 583, pl. 20, figs. 31, 32.

RECORDS: Halibut Oil Platform, eastern Bass Strait, mid-littoral and 10 m deep, on mussels *Mytilus edulis planulatus* (Lamarck), coll. Natural Systems Research Pty. Ltd., June, 1975; Cowes, Westernport Bay, on *Sargassum*, 3 m deep, (24/10/71); Popes Eye reef, on sponge, 10 m deep, (20/8/76): both collections, J.E. Watson.

REMARKS: Von Lendenfeld (1884) described *Sarsia radiata* from medusae collected from Port Jackson which he reared through to the hydroid stage, and a hydroid without medusa from the 'laminarian zone' in Port Phillip Bay. There have been no further records of this hydroid since his original description. The lack of records of what now proves to be a relatively common species is perhaps not surprising, as it is difficult to deduce the true nature of the medusa from von Lendenfeld's description and recent collections of fresh material have shown that the hydroid stage is either morphologically very variable, or not well described from the original material.

The tentacles of the medusa, described by von Lendenfeld as 'a little larger than the ocellar bulbs' are shown in his figure as three times the length of the bell, and further, show no sign of the nematocyst clusters or the capitate ends characteristic of *Sarsia*. Medusae liberated from living hydroid colonies collected at Popes Eye reef were observed for two days before death. These displayed sufficient similarity to von Lendenfeld's description and figure of *S. radiata*, in the shape of the bell and stomach, to warrant considering them to belong to this species. The smaller dimensions of the Popes Eye medusae (0.75 mm high, 0.65 mm wide) compared to those of von Lendenfeld (3 mm high, 2.5 mm wide), and the colour differences between manubrium and tentacle bulbs (brown in von Lendenfeld's material, golden in the Popes Eye specimens) could be due either to age or to geographical factors. Although von Lendenfeld nowhere mentions the age of his medusae, it is assumed that his observations were of adult specimens. It is surprising that he fails to mention the bright orange ocelli, a prominent feature of the present specimens.

The hydrorhiza of the hydroid phase is described by him as 'anastomosing', with unbranched stems, brownish coloured perisarc, and hydrocaulus terminating below the hydranth with an oblique margin. The hydranth comprised 6-8 verticils of four tentacles (= 24-32). Although his hydroid material from Port Phillip Bay was infertile, he considered the specimens to be conspecific with *S. radiata* from Port Jackson. The parent hydroid colony associated with the medusae of *S. radiata* collected by the author at Popes Eye reef fails to conform in several respects with von Lendenfeld's description of the hydroid of *S. radiata*; in fact it more closely matches his description of the hydroid of *Sarsia minima* von Lendenfeld, 1884, also from Port Jackson. Most of the material collected from various localities in Westernport Bay, Bass Strait and Port Phillip Bay in Victoria have tentacles clearly arranged in verticils, but the number never exceeds 16, that is, half the maximum described for *S. radiata* by von Lendenfeld. Two single infertile stems also collected from Westernport Bay, and another from Portland in western Victoria (both collections by the author) have hydranths with 24 and 12 tentacles respectively. All this material, while closely resembling *S. radiata* as now known, is infertile, but until fertile material is found and medusae observed, it is not possible to decide if the hydroid of *S. radiata* is indeed a very variable species, or whether in fact, several species are involved.

With information from the wider range of material now available, a redescription of *S. radiata* is given below.

DIAGNOSIS: Hydroid. Hydrorhiza cylindrical, 0.15-0.25 mm in width, creeping on surface of hard substrate, or embedded in the surface of sponge or compound ascidians. Perisarc of hydrorhiza may be thin or quite thick, depending on age of colony. Stems reaching 5 mm in height, 0.12-0.15 mm in width, perisarc variable in thickness, usually thicker proximally, becoming thinner distally, either entirely ridged throughout, annulated, or occasionally, smooth. Stems may be simple, or with one

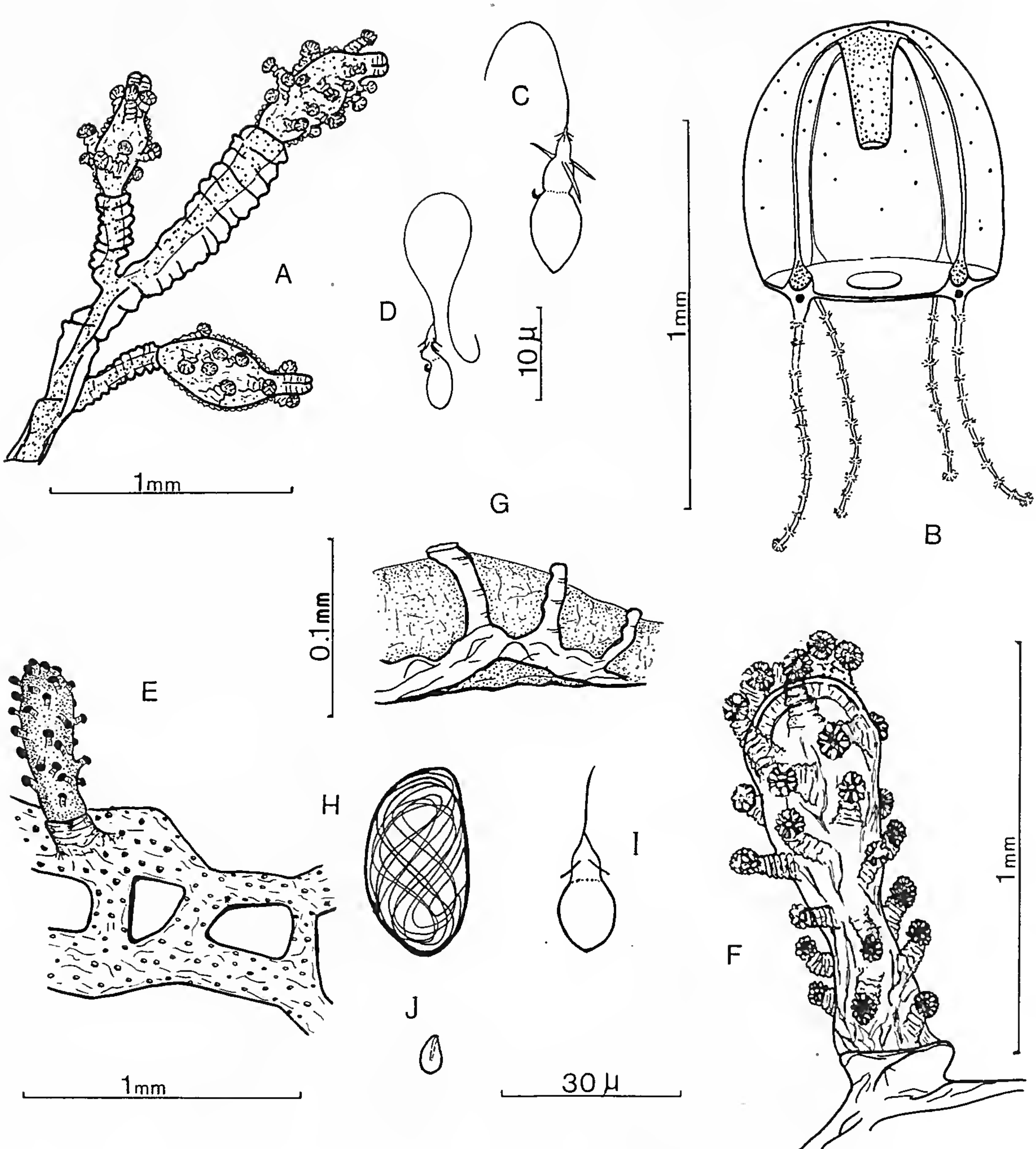

FIG. 2 — *Sarsia radiata* von Lendenfeld, 1884. A, part of colony from Halibut Oil Platform, eastern Bass Strait; B, newly liberated medusa from colonies from Popes Eye reef, Port Phillip Bay, Victoria; C, D, nematocysts from hydroid stage — C, stenotele; D, microbasic eurytele. *Rosalinda marlina* n.sp. E, reticulate hydrorhiza with perisarcal spines and hydranth on barnacle *Balanus trigonus* Darwin: F, hydranth seated in perisarcal cup; G, section through hydrorhiza showing perisarcal tubes extending through hydrorhiza to surface; H–J, nematocysts from hydrorhiza — H, large mastigophore, undischarged; I, stenotele with short spines; J, small ?isorhiza, undischarged.

or two short branches, hydranths terminal. Hydranths spindle shaped in extension, 0.8-1 mm in length, with 12-16 capitate tentacles in 4 or 5 irregular verticils, including 4-5 tentacles around the hypostome. Fertile hydranths contracted, with up to 6 medusa buds in various stages of development.

COLOUR: Body of hydranth orange-pink, tentacles translucent white.

Nematocysts of two types present in hydroid:

— stenoteles, moderately abundant, capsule oval, butt about two thirds length of capsule with 3 long barbs. Length of capsule 7.5μ, width 5μ.

— microbasic euryteles, very abundant, capsule oval, length 4μ, width 2μ, butt about same length as capsule.

MEDUSA: Newly liberated medusa deep bell shaped, symmetrical, umbrella deeper than wide, 0.75 mm high, 0.65 mm wide, jelly moderately thick, apical knob not present. Velum very broad, stomach cylindrical or slightly tapering, less than half the length of bell, mouth simple, circular. Gonads not developed at this stage. Four simple radial canals present, circular canal narrow, passing around the adaxial side of the marginal bulbs. Marginal bulbs large, with well developed ocelli. Tentacles extensile, about same length as bell when fully extended, in contraction about same size as marginal bulbs, with regularly spaced clusters of nematocysts with a large capitate end. Scattered nematocysts on bell in interradial areas, concentrated mainly in the apical region.

Nematocysts of two types present in medusa:

— stenoteles of same shape but larger than those of the hydroid, capsule 11μ long, 8.5μ wide,

— very abundant ?microbasic euryteles, not discharged, 10μ long, 5-7μ wide.

COLOUR: Umbrella and tentacles colourless, stomach deep orange apically, grading through golden to almost colourless at mouth; marginal bulbs golden, ocelli deep orange.

S. radiata is unusual among the *Sarsia* in having microbasic euryteles and not desmoneme nematocysts in both hydroid and medusa.

The range of *S. radiata* is now extended from the Sydney region south to Bass Strait and the Victorian embayments.

Family ZANCLEIDAE

Rosalinda marlina n.sp.

(Fig. 2, E-J.)

TYPE MATERIAL AND RECORDS: Holotype, NMV G2804, microslide, G2805, preserved material, remainder of holotype colony, on ascidian, 36 m deep; paratype, G2806, microslide, on barnacle *Balanus trigonus* Darwin, 10 m deep, all material from Marlin Oil Platform, eastern Bass Strait, coll. Natural Systems Research Pty. Ltd., June 1974.

DESCRIPTION FROM HOLOTYPE AND PARATYPE: Hydrorhiza an encrusting mat of coenosarc which may be continuous or reticulating depending upon the nature of the substrate, but enveloping pre-existing material such as the stolons of other hydroid species. Hydrorhiza closely following the contours of the underlying substrate, but not strongly adherent, being separated from it by a very thin chitinous sheath. Upper surface of hydrorhiza uneven, with rare blunt ectodermal prominences and numerous small projecting hollow chitinous spines. The spines comprise thick brown coloured perisarc, 0.01-0.02 mm diameter, originating in the coenosarc and may be entirely solitary, or connected together in groups of 2-4 by small chitinous tubes about the same diameter as the spines, or they may arise from an incipiently developed chitinous trabeculate meshwork buried within the coenosarc.

Hydranth club shaped or cylindrical (in contraction), 1.25-2 mm in length (preserved), greatest width 0.15-0.3 mm, usually in distal third, hypostome dome shaped. Tentacles 40-45 in number, capitate, scattered over hydranth, with highest density in the region of the hypostome, but not comprising an oral whorl. Extended tentacles 0.13-0.18 mm long, stout, wrinkled, capitulum 0.04-0.06 mm diameter, richly supplied with nematocysts. Hydranth entirely naked, or seated on a rudimentary hydrophore of ectodermal origin reaching 0.1 mm high.

Nematocysts of three kinds present:

— large bean shaped mastigophores, all undischarged, 25 x 15μ – 30 x 20μ, very abundant, especially around the base of the hydranth,

— stenoteles, capsule round, 10 x 8 — 11.3 x 8.8μ, not clearly seen but some discharged; scattered throughout coenosarc of hydrorhiza,

— small ?isorhizas, none discharged, capsule 5 x 3.8μ, scattered throughout hydrorhiza, and probably also in the tentacles.

REMARKS: The genus *Rosalinda* was erected by Totton (1949) for the reception of *Rosalinda williami* Totton, 1949, an epizoic hydroid displaying no polymorphism, and of encrusting habit. The two species so far recorded in this genus are *R. williami* and *R. incrustans* Kramp, 1947. The characteristics of the genus and both species comprising it were redescribed and discussed in detail by Vervoort (1966), who considered that the trabeculate framework of the hydrorhiza, permeated by the coenosarc, was evidence of affinity with the Solanderidae. He earlier (1962) commented on the presence of 'giant nematocysts' in the basal encrustation and later described them in more detail (Vervoort 1966), commenting that 'so far, *Rosalinda* seems to be the only hydroid genus endowed with macrobasic mastigophores'.

Bouillon (1974) considered the possession of these nematocysts to be a far more important characteristic for family definition than the character of the hydrorhiza and accordingly transferred *Rosalinda* to the Zancleidae. The opinion of Bouillon is accepted here; however there is still no information upon the reproductive structures which would allow a final decision to be made on the familial status of the genus.

Two structures found in the limited material available

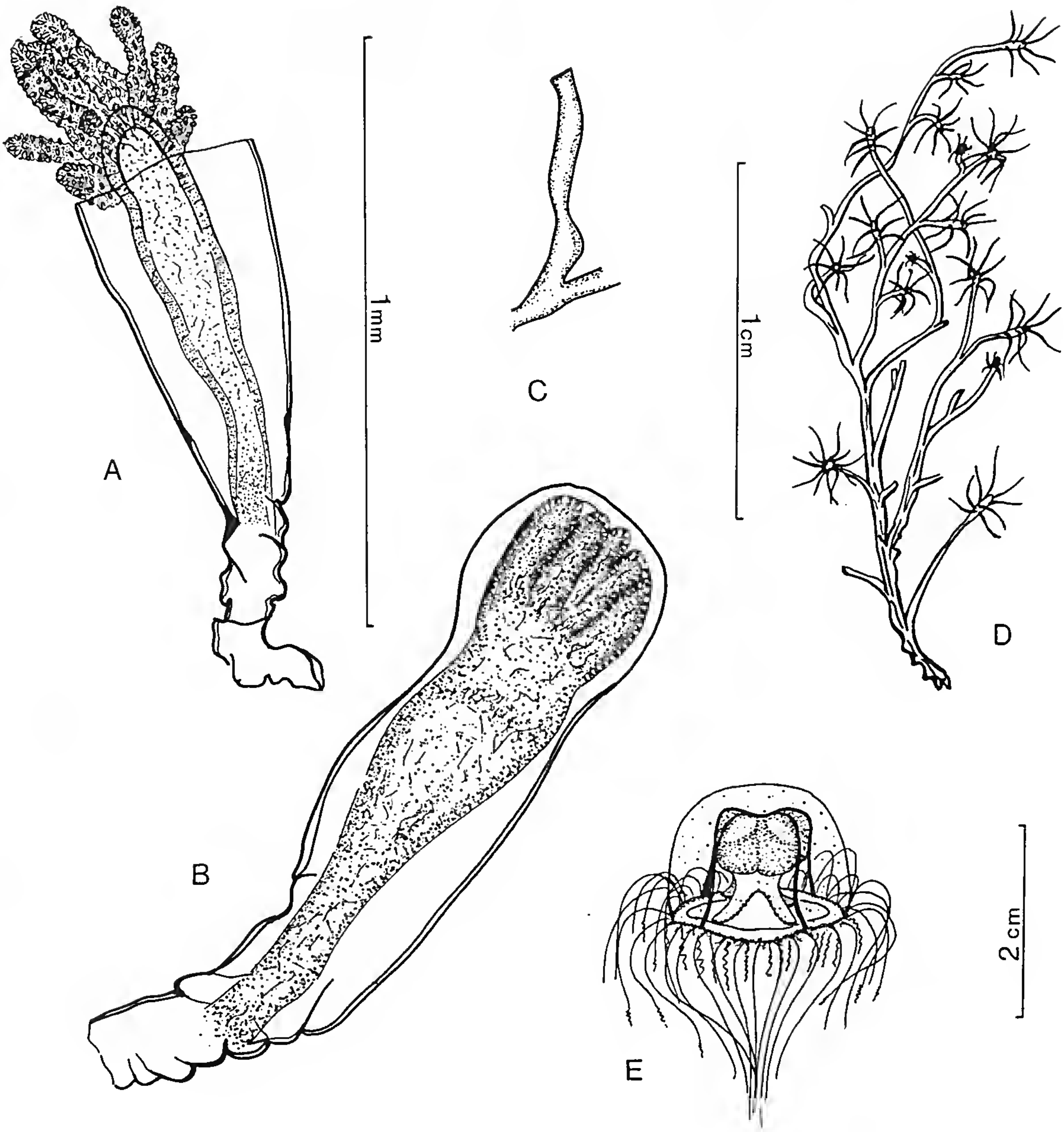

FIG. 3 — *Merona operculata* n.sp. A, tube with partially extended hydranth; B, tube with immature hydranth, hydrotheca sealed by a dome shaped operculum; C, nematotheca. (A–C drawn to same scale.) *Turritopsis nutricula* McCrady, 1856. D, part of colony from Westernport Bay, Victoria, drawing from photograph of living colony *in situ*; E, medusa with well developed gonads and numerous tentacles, drawn from living specimen from Backstairs Passage, South Australia.

for study could possibly be dactylozooids, but due to extraneous growth and the investing nature of the hydrorhiza, these could not be ascribed with any certainty to the hydroid. Should further material show conclusively the presence of polymorphism among the colonies of *R. marlina*, then the species should rightly be transferred to *Teissiera* Bouillon, 1974.

Vervoort (1966) described *R. williami* as having a plate-like skeleton resulting from the junction of a rectangular meshwork of internal walls, the upper surface of which are sometimes produced into ribs and short rounded spines. In *R. incrustans* the ribs are less elevated at the surface of the hydrorhiza, the protrusion of the ribs and spines seemingly being more an expression of the topography of the underlying substrate than a primary structural character of the hydrorhiza. Except for one small area where there are a few incipiently developed buttress-like chitinous walls within the coenosarc, the hydrorhiza of *R. marlina* is entirely devoid of the trabeculate framework described for either *R. williami* or *R. incrustans*. Further, the hollow spines in *R. marlina* have no counterpart in the other two species, the spines of *R. williami* being short and rounded, while in *R. incrustans* spines of autochthonous origin seem to be absent (Vervoort 1966). The abundant slender tubular spines of *R. marlina* have a thick strong perisarc, and where the chitinous internal meshwork is developed, the spines arise directly from these structures. Where the meshwork is absent, groups of 2-4 spines are joined together at their bases by irregularly winding short tubes. Some spines are solitary, and these arise directly to the surface from the underlying chitinous basal membrane of the hydrorhiza.

As in *R. williami* and *R. incrustans*, the hydrorhizal coenosarc of *R. marlina* is richly supplied with nematocysts. Vervoort (1966) records macrobasic mastigophores and stenoteles of two sizes in *R. williami*, while in *R. incrustans* there are numerous isorhizas as well. The macrobasic mastigophores of *R. marlina* are the smallest of the three in size, and the stenoteles are about the same size as the smaller ones of *R. williami* and *R. incrustans*. The numerous very small but undischarged nematocysts of *R. marlina* are thought to be isorhizas since they strongly resemble the isorhizas of *R. incrustans* in shape, although they are only half the size of those of the latter species.

A comparison of the nematocysts and their dimensions in the three species is given below. Dimensions are in μ.

Species	Macrobasic Mastigophores	Stenoteles (large)	Stenoteles (small)	Isorhizas
R. williami	24 x 36	18 x 25	9 x 13	
R. incrustans	25 x 35	22 x 18	10 x 7 – 13 x 9	8 x 18
R. marlina	15 x 25 – 20 x 30		10 x 8 – 11 x 9	4 x 5

In size of the hydranth, number of tentacles and general aspect of the colony, *R. marlina* shows a greater resemblance to *R. incrustans* than to *R. williami*. However the difference in size of the nematocysts, the presence of tubular spines and the general structure of the hydrorhiza clearly distinguish *R. marlina* from both species.

R. marlina and *R. incrustans* are both epizoic species, *R. marlina* being taken in shallow water at a depth of 10 m on the shell of a barnacle, and at 36 m on an ascidian; *R. incrustans* was taken from a crab collected at a depth of 225 m in the North Sea. *R williami*, while not strictly epizoic, is also a deep water species, collected from a cable at a depth of 440 m in the Bay of Biscay.

This is the first record of the genus from the southern hemisphere.

Family Clavidae

Merona operculata n.sp.

(Fig. 3, A–C.)

Type Material and Records: Holotype, NMV G2807, microslide, Crawfish Rock, Westernport Bay Victoria, 10 m deep, on compound ascidian *Didemnum patulum* (Herdman), coll. J.E. Watson, 30/7/67.

Description from Holotype: Gastrozooids sheathed in a firm conical tube which may be straight or curved, perisarc of the tube moderately thick, strongly wrinkled proximally, smooth or a little undulated distally, aperture transverse. Length of tube 0.88–1.25 mm, width at aperture, 0.27–0.35 mm. Hydranth extensile, capable of contraction into tube, with about 10 filiform tentacles surrounding a club-shaped hypostome. Tentacles 0.15 mm long fully extended, with a clearly defined distal cap 0.04–0.05 mm wide richly armed with nematocysts (type unknown).

Nematophores present, supported on a long tubular pedicel of perisarc 0.4 mm long arising from the hydrorhiza, distal end widening slightly to form nematotheca. Diameter of nematotheca 0.05 mm. No nematocysts present in empty nematotheca.

Gonophores absent. Colour unknown.

Remarks: The small sample available in this collection is infertile and is devoid of any extensive hydrorhiza. A small fragment adhering to the base of one perisarcal tube suggests that the hydrorhiza may be tubular in structure. One hydrotheca containing an immature hydranth is enclosed in a dome shaped structure continuous with the perisarc of the tube. This protective 'operculum' apparently breaks away along a line of weakness marked by inflexure across the wall of the tube, allowing emergence of the mature hydranth.

In the absence of fertile material it is difficult to make a decision as to whether clavate hydroids with a protective tube belong to *Tubiclava* or *Merona*. However the retractable hydranths and the single nematotheca arising from the hydrorhiza provide sufficient basis for reference of this species to *Merona*.

Merona cornucopiae (Norman 1864) has been the only species of the genus so far recorded. It has been fully

described and discussed by a number of authors (Kramp 1935, Cabioch 1965, Christiensen 1972, Millard 1975). It has a wide distribution in the northern hemisphere, including the North Sea, North Atlantic, Mediterranean, Pacific and Atlantic coasts of North America; it has been recorded in the southern hemisphere only from South Africa. *M. cornucopiae* is usually associated with living molluscs.

While generally similar to *M. cornucopiae*, *M. operculata* has fewer tentacles than the minimum of 16 recorded for *M. cornucopiae*, and these are concentrated in the oral region, in contrast to the scattered distribution characteristic of *M. cornucopiae*. The tube of *M. operculata* is similar in width to *M. cornucopiae*, but is much shorter, and is heavily wrinkled in the proximal region. The single nematotheca also comes within the size range of *M. cornucopiae*, but the funnel-shaped distal end characteristic of that species is absent.

This is the first record of the genus from Australian waters and the first record of its association with an ascidian.

Turritopsis nutricula McCrady, 1856

(Fig. 3, D, E.)

Oceania (*Turritopsis*) *nutricula* McCrady, 1856: 55, pls. 4, 5.
Turritopsis lata von Lendenfeld, 1884: 588, pl. 22, fig. 36.
Turritopsis chevalensis Thornley, 1904: 109, pl. 1, fig. 4. Stechow, 1924: 69; 1925: 198.
Turritopsis dohrni Blackburn, 1937: 178, figs. 15, 16.
Turritopsis nutricula Russell 1953: 115, figs. 54–56, pl. 5, figs. 1–5, pl. 29, figs. 1–3. Millard, 1975: 76, fig. 24 F–G.

REMARKS: Stechow (1925) recorded *Turritopsis chevalensis* Thornley, 1904, from Shark Bay and the mouth of the Swan River, Western Australia, remarking that further collections would be likely to prove that *T. chevalensis* and *T. dohrni* are synonyms of *T. nutricula* McCrady, 1856. Blackburn (1937) recorded this hydroid as *T. dohrni* Weissmann, 1883, from Westernport Bay, Victoria. Blackburn's material was meagre, and although fertile, it was insufficiently mature to enable him to diagnose accurately the medusoid structure of the gonophores.

Observations by diving, over several years, have established that *T. nutricula* is one of the commonest hydroids in the sheltered waters of Westernport Bay, where it grows abundantly on invertebrate and algal substrates on reef and man-made structures between 3 and 25 m depth. It has also been observed by the author in ocean waters of Victoria and New South Wales at various depths where it grows in situations of low light intensity under ledges, in caverns, and in cavities in the underside of flat boulders on the seabed. The strongly fascicled colonies grow to a height of 3–4 cm during the winter months. The hydranths are rose pink and the tentacles white.

The medusa of *T. nutricula* has been known from South Australian waters for many years where it occurs in dense swarms during the summer months (January to March). The adult medusa is 1.5–2 cm across the bell, has at least 100 tentacles, and the large gonads are rose red. The medusa is an energetic swimmer. The hydroid stage is so far unrecorded from South Australia.

Von Lendenfeld's (1884) description of the medusa of *T. lata* from Port Jackson, and his comments on its swarming habit during the summer months leaves no doubt that *T. lata* is a synonym of *T. nutricula*.

New records of hydroid and medusa now extends the range of this cosmopolitan species around the southern half of Australia from Sydney to Shark Bay. It has not yet been recorded from Australian tropical waters.

Bimeria australis Blackburn, 1937

(Fig. 4, A–F.)

Bimeria australis Blackburn, 1937: 177, figs. 10–12. Pennycuik, 1959: 164.

RECORDS: Popes Eye reef, Port Phillip Bay, 7 m deep, on octocoral *Telesto smithi* (Gray) and hydroid *Parascyphus simplex* (Lamouroux), coll. J.E. Watson, 31/5/76; North Arm channel, Westernport Bay, 3–15 m deep on bryozoa *Amathia biseriata* Krauss, on solitary and compound ascidians and other hydroids (J.E. Watson, 1973, 1976); Portland, Victoria, on *A. biseriata*, 7 m deep (J.E. Watson, 9/6/68); 80 km off Warrnambool, Victoria, 310 m deep, on compound ascidian (V. Johnstone, 14/5/69).

MATERIAL: All specimens conform to Blackburn's description of *Bimeria australis*. The following observations augment Blackburn's description.

Maximum length of stems, 4 mm, branching irregularly alternate, a single hydranth usually terminal on branch. Stem and branches may be annulated or wrinkled, the annulations being more distinct proximally, but parts of stems, particularly those from deeper water, may be smooth. Hydranths not distinctly set off from stem, but this is frequently difficult to observe due to infolded habit of tentacles when preserved, and the heavy coating of foreign matter on and below the hydranth. The proximal half of the tentacles of preserved specimens is always obscured by adherent agglutinated material, but close-up underwater photographs show that in life the tentacles are capable of considerable extension beyond this protective sheath.

Gonophores arising singly on a short pedicel from stems, branches and hydrorhiza. Mature gonophores 0.2–0.28 mm diameter, globular or sometimes slightly flattened in section, covered in a thick gelatinous envelope heavily coated in foreign material. Male and female gonophores fixed sporosacs, borne on same stems, female with a bright red spadix in the proximal region supporting a single egg which develops into a planula *in situ*. Male gonophore spherical; radical canals and tentacles rudiments absent.

Nematocysts rare in hydroid, of three types:

— large stenoteles, capsule oval, 7 x 5.5 –10 x 9 μ, butt about half the length of capsule,

— smaller stenoteles, capsule spherical, very rare, 3 μ diameter,

— microbasic mastigophores, capsule bean-shaped, 7 x 4.5 μ in length, tube long.
The stenoteles are concentrated in the tentacles and the mastigophores are scattered throughout the coenosarc of the hydrocaulus.

COLOUR: The colonies are uniformly buff coloured from the adherent matter, but parts of the hydranths visible are pinkish and tentacles white (from colour photographs *in situ*); gonophores white, spadix of female bright red. Specimens from deeper water are more uniform pink in colour than those from shallow water.

REMARKS: This is a very common epizoic species occurring during late winter months (July-September) in Victorian waters when temperatures are lowest. It occurs in large colonies in sheltered situations in embayments where light penetration is poor, such as jetties, and in caverns and under rocks in the ocean. It frequently occupies the same habitat as *Turritopsis nutricula*.

Nematocysts are extremely rare in *B. australis*. Possibly the protection afforded to the hydranths and gonophores by the thick encrustation of foreign material obviates the necessity for production of large concentrations of nematocysts.

B. australis is now known from the embayments, coastal, and deeper waters of the Victorian coastline. Further collections will almost certainly extend its range westwards along the southern coastline.

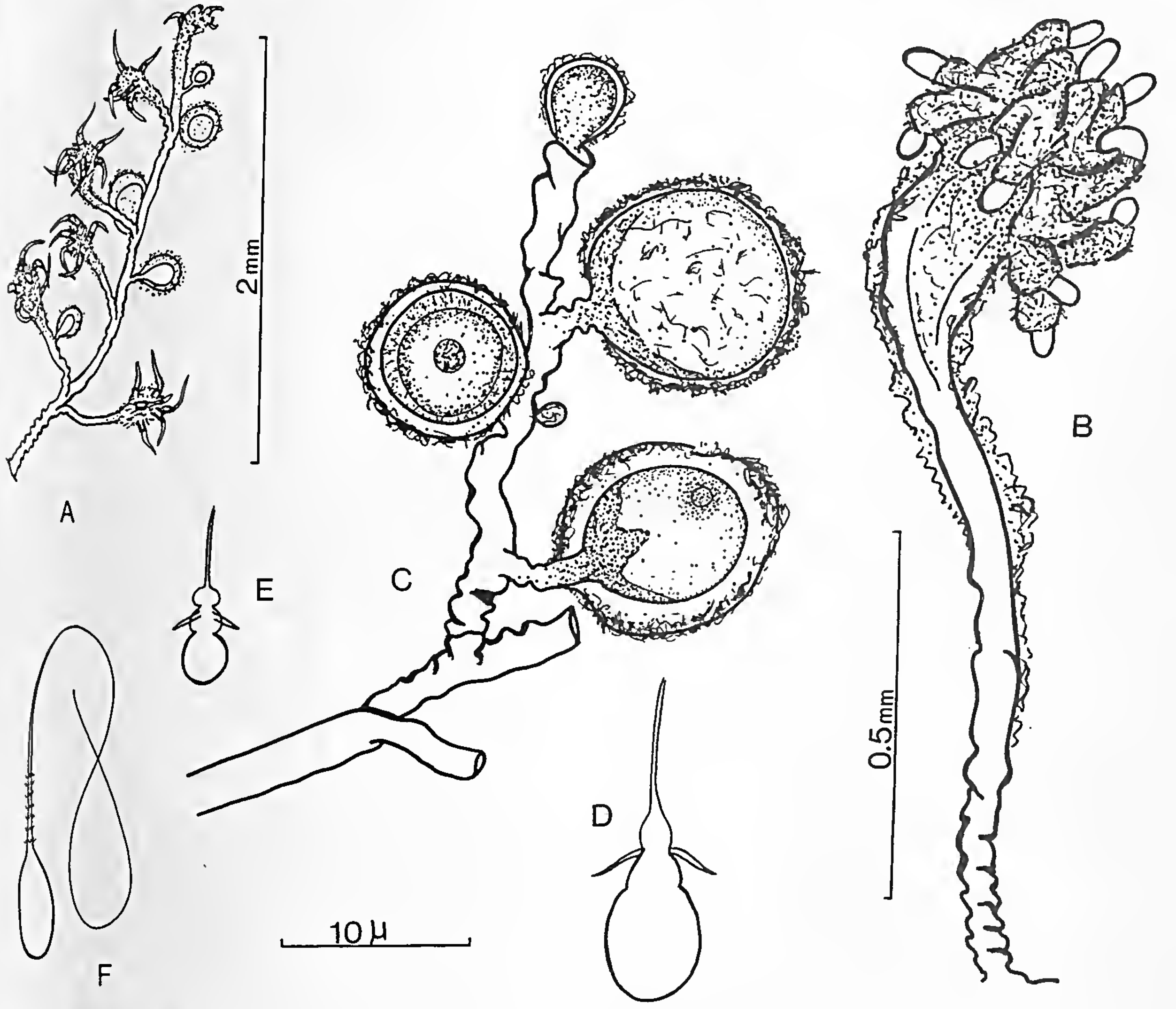

FIG. 4 — *Bimeria australis* Blackburn, 1937. A, typical fertile stem from Westernport Bay, Victoria, drawn from photograph of living colony *in situ*, showing extension of tentacles in life; B, enlargement of hydranth from preserved material from Popes Eye reef, Port Phillip Bay, Victoria, showing body and tentacle sheaths with covering of adventitious matter; C, fertile stem with one male and two female gonophores, each female gonophore containing a single ripe egg (B and C drawn to same scale); D—F, nematocysts from hydranth — D and E, large and small stenoteles; F, microbasic mastigophore.

Stylactis betkensis n.sp.

(Fig. 5, A–H.)

TYPE MATERIAL AND RECORDS: Holotype, NMV G2808, microslide, female colony on gastropod *Parcannassa burchardi* (Philippi); NMV G2809, preserved material, remainder of holotype collection. Paratype, NMV G2810, preserved male and female colonies from same collection. Betka River, Mallacoota, Victoria, in estuarine section, just subtidal in *Zostera muelleri* beds. Coll. R. Plant, February, 1973.

DESCRIPTION FROM HOLOTYPE AND PARATYPES: Colonies comprising gastrozooids and gonozooids arising from a reticulate hydrorhiza following the hollows and sutures of the host shell. Hydrorhiza cylindrical, approximately 0.1 mm diameter, perisarc brown, moderately adherent to shell. Gastrozooid variable in shape and length but usually rather long, reaching 1.2 mm (preserved), slender proximally, expanding to maximum width midway or in distal third of length, then contracting to hypostome. Hypostome well defined, with four radially disposed segments which extend longi-

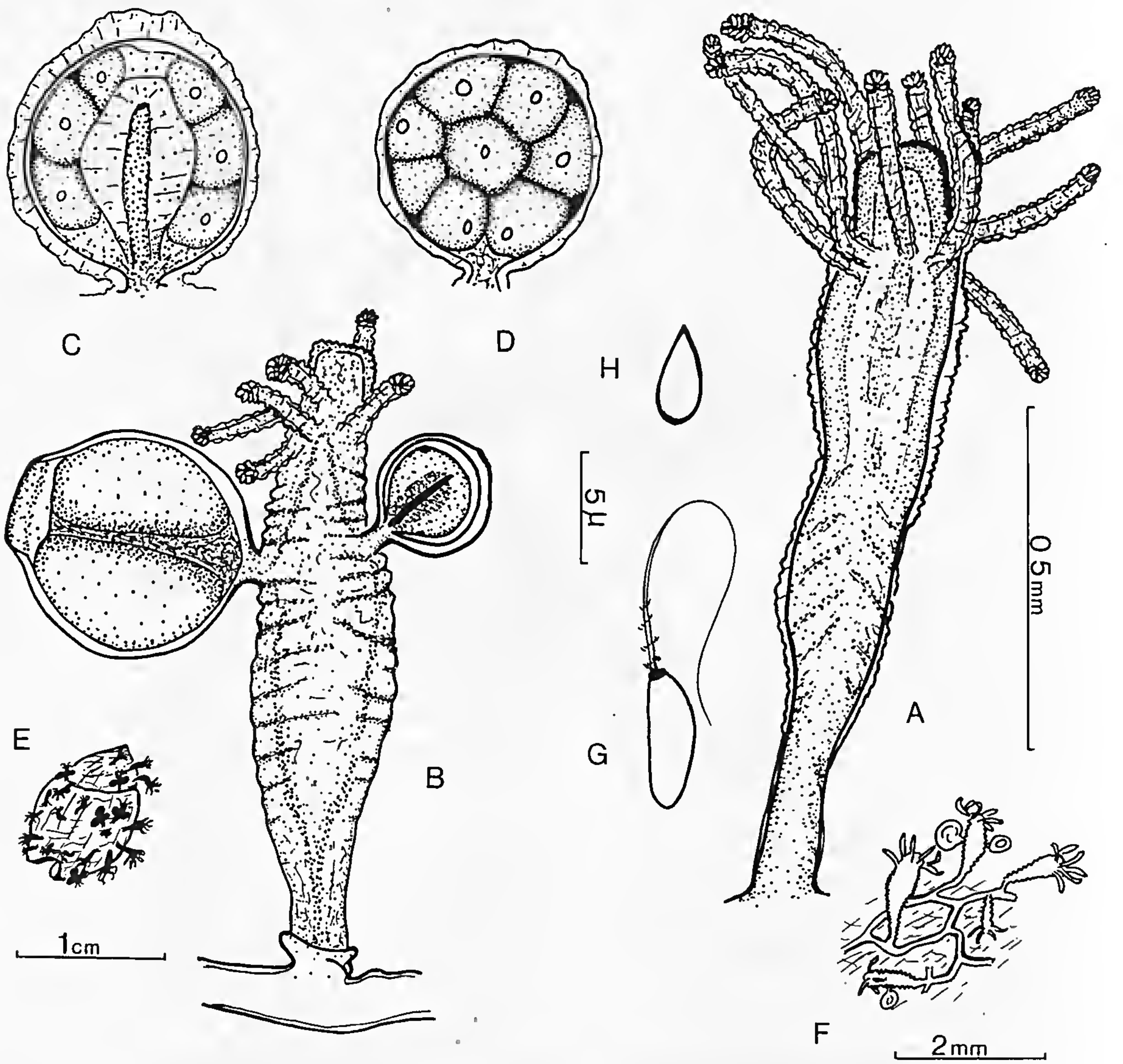

FIG. 5 — *Stylactis betkensis* n.sp. A, gastrozooid, B, gonozooid with male gonophore; C and D, stages in development of female gonophore from cleared whole mounts — C, young gonophore with eggs surrounding spadix; D, mature gonophore entirely filled with eggs (A–D drawn to same scale); E, colony on gastropod shell, *Parcannassa burchardi* (Philippi); F, part of colony on shell; G, H, nematocysts — G, ?basitrichous isorhiza, H, ?eurytele.

tudinally through the body of the hydranth as four moderately well defined canals. Tentacles 8–15 in number, reaching 0.3 mm in length (preserved), situated in a single whorl below hypostome, distal ends a little expanded and richly armed with nematocysts.

Nematocysts of two types present in gastrozooid:

— ?basitrichous isorhizas, very abundant, very few discharged, capsule bean shaped, 6.5 x 2.5 μ,

— smaller ?euryteles, less abundant, none discharged, capsule top-shaped, 4.5 x 2.5 μ.

Gonozooids rare, usually shorter than gastrozooid, 0.65–0.8 mm in length (preserved) with about 8 tentacles and up to 5 gonophores in different stages of development borne on short stalks arising from the thickened region below the tentacles, body of gonozooid frequently strongly contracted into transverse rings below whorl of gonophores.

Gonophores round or oval, male and female on separate colonies, mature gonophores reaching 0.4 mm diameter, enclosed in a tough transparent ectoderm of uniform thickness except for a thickening at the raised and flattened distal end. Immature gonophores with 4 radial canals. Mature female gonophore cryptomedusoid with 12 large eggs arranged around the radial canals, the eggs expanding at maturity to fill the entire cavity.

COLOUR: Living colonies white, perisarc of hydrorhiza brown, gonophores creamy white.

REMARKS: The absence of tentaculozooids, and even in the older colonies, the absence of a crustose layer of coenosarc over the hydrorhizal tubes clearly distinguishes this hydroid as belonging to *Stylactis*. Both hydrorhiza and proximal parts of the zooids are deeply immersed in a layer of flocculant white material covering most of the gastropod shell. A similar deposit was noted by Pennycuik (1959) surrounding the base of gastrozooids and gonozooids of *Stylactella niotha* Pennycuik 1959, from Queensland. In the present instance the flocculant material is so thick and extensive, even in parts of the shell where the hydroid has not penetrated, that it seems unlikely to be anything other than an adventitious association. Such an association would however, offer considerable protection to the hydrorhiza and stems of the hydroid colony.

Stylactis betkensis resembles *S. inermis* Allman, 1872, and *Stylactella* (*Stylactis*) *yerii* Iwasa, 1934. Reproduction of all these species is through a cryptomedusoid stage, but according to Iwasa (1934) the sporasac of *S. inermis* passes through the cryptomedusoid to a eumedusoid stage. This has not been observed in *S. betkensis*. The gastrozooid of *S. inermis* has 20 tentacles, compared to a maximum of 15 in *S. betkensis*, and the colonies of the former are reported to bear nematophores (Stechow 1923). Iwasa's revision of the genus, extended to include species added since 1934 is summarized by Bouillon (1971).

Even when adequate fertile material is available for study it is sometimes difficult to distinguish between species of certain athecate hydroids from the literature alone. In the present instance, a few characteristics of largely unknown diagnostic importance, such as the greater number of tentacles of the gonozooid (8 in *S. betkensis*, 4 in *S. yerii*), the larger mature gonophore and the distinctive pedunculate stalk of *S. betkensis* are the only characteristics which serve to distinguish between the two species. Nematocysts which would possibly provide more definitive information were not described by Iwasa for *S. yerii*, and there is also doubt as to the types of nematocysts present in *S. betkensis*.

Known from a depth of 140 m at only one locality (Misaka, Japan), *S. yerii* is fully marine, in contrast to *S. betkensis*, which occurs in brackish shallow water estuarine conditions.

This is the first record of *Stylactis* in Australian waters.

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30

THE VEGETATION AT WALKERVILLE, VICTORIA

A Further Application of the Zürich-Montpellier Technique

By P. D. CHEAL*

ABSTRACT: The native vegetation of the Cape Liptrap-Walkerville area is classified using the Zürich-Montpellier system of phytosociology. Eight distinct plant communities are distinguished and their regional relationships discussed. The primary determinants of these communities appear to be various edaphic factors, particularly the nutrient status and fluctuations in the depth of the water-table. Although the dominants may be differential species of these communities, their distributions are frequently unrelated to community boundaries and their use as the sole community determinants elsewhere is questioned.

INTRODUCTION

The Cape Liptrap-Walkerville area is a small remnant of uncleared land surrounded by cleared pasture, on the coast immediately west of Wilsons Promontory, Victoria. The Cape itself is a rocky headland jutting out into Bass Strait, with long stretches of more or less consolidated high dunes on the western side, and a coastline of high cliffs and rocky bays and beaches on the eastern side. It is one of the few remaining sizeable areas of native vegetation between Port Phillip Bay and Wilsons Promontory which had not been studied from the botanical point of view.

The aim of this investigation was to provide a workable vegetation classification. The Zürich-Montpellier system of phytosociology seemed to provide the most comprehensive analytical procedure and was chosen for this purpose. The relative advantages and disadvantages of the Zürich-Montpellier system have been adequately discussed elsewhere (Poore 1955a, b, c, 1956, Moore 1962, Greig-Smith 1964, Moore *et al.* 1970 and Gullan 1975). Broadly, it is an easily used, universally understood and non-subjective phytosociological system. Furthermore, as the species involved become better understood the particular species assemblages outlined indicate much about the local environment (e.g. rainfall, edaphic conditions, frequency of fires, grazing pressure) and also give an indication of the regional relationships and recent history of the flora.

CLIMATE

The Cape Liptrap – Walkerville region experiences the uniform climate expected at an exposed maritime location. Data from the Wilsons Promontory recording station, which is likely to experience a similar climate, shows the hottest months to be January and February with mean maxima of 20.1°C and 20.7°C and mean minima of 13.8°C and 14.5°C, respectively. This small difference between the mean monthly maxima and minima is also found in the coldest month, July, when the mean maximum is 12.3°C and mean minimum 8.1°C. Occasional extreme temperatures are experienced in summer; the highest recorded being 41.4°C in January. The maritime location apparently exerts a greater influence on minimum temperatures than it does on maximum temperatures. Minima less than 2°C are only very rarely reported. The lowest recorded (June) minimum is −1.1°C. Frost rarely if ever occurs.

The mean annual rainfall recorded at Walkerville is 1026 mm (1039 mm at Wilsons Promontory), and is more or less evenly distributed throughout the year, with a moderate winter maximum. July is the wettest month with a mean monthly rainfall of 121 mm and February the driest with 38 mm. However, the mean summer (December to February) rainfall is relatively high at 157 mm. The chance of receiving rainfall equal to or greater than the 'effective amount' (see Gibbs 1951) is quite high in all seasons except summer.

*Departments of Zoology and Botany, Monash University, Victoria.
Current address: National Parks Service (Victoria), 240 Victoria Parade, East Melbourne, Victoria 3002.

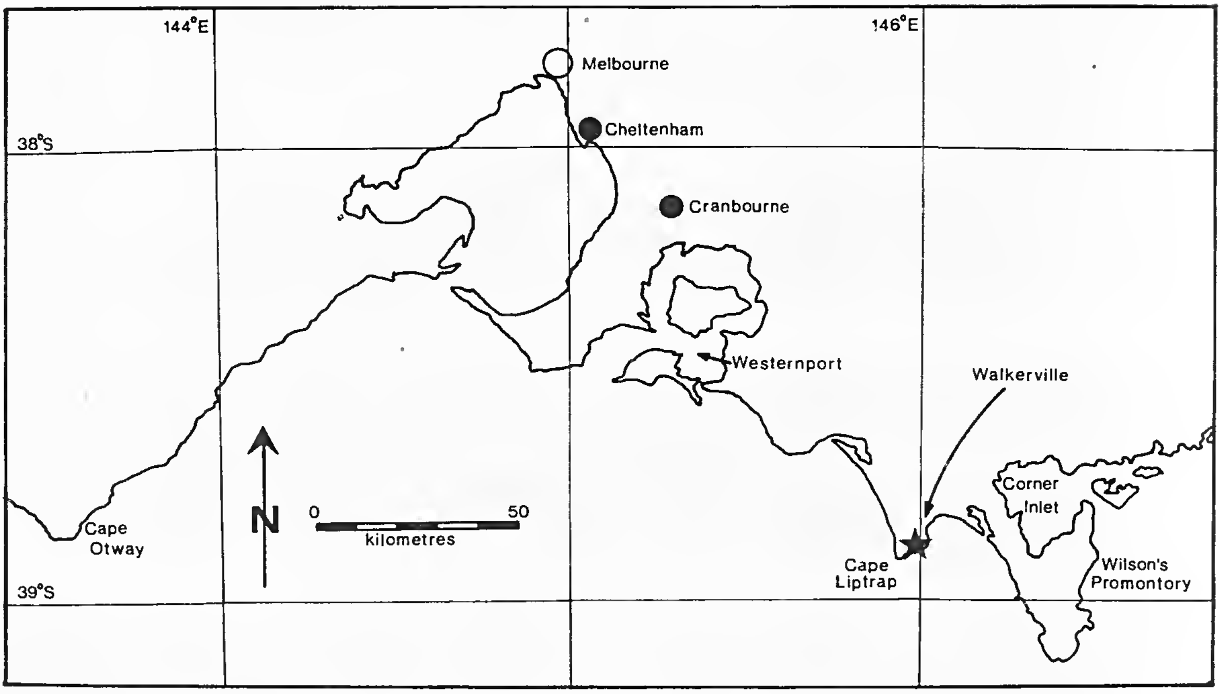

FIG. 1 — Location of Study Area (and selected localities mentioned in the text).

For Wilsons Promontory the percentage chance of receiving effective rainfall in this period is 78% for December, 59% for January and 62% for February. Droughts (i.e. consecutive months of less than effective rainfall) are infrequent. Dry periods lasting two to three months have been recorded between November and March but are not common.

Although dependent on local weather conditions, hours of sunshine vary from 200 to 250 hours for each summer month to between 100 and 150 hours for each winter month.

In summary, the climate is remarkably uniform and rarely experiences either extended periods of rainfall deficiency or extremes of temperature.

PHYSIOGRAPHY

The predominant geological feature is the Liptrap Formation, a dark grey Lower Devonian mudstone/shale that is extremely well-bedded. Sandstone, grit and pebble bands, to greater than 1 m thick, are rhythmically interbedded and there are sporadic massive units of gritty and pebbly sandstone (Singleton 1973). The strike is more or less constant to the north, with dips generally fairly steep to the west. Occasional slump conglomerates with pebbles of chert, jasper and greenstone contain limestone boulders probably originating from the Waratah Limestone. This limestone is a massively bedded Lower Devonian deposit outcropping rarely and mostly covered by Tertiary deposits (Douglas 1972/5).

Overlying much of the Palaeozoic deposits are semi-consolidated or compacted sandy gravels and sandstone conglomerates of Pliocene alluvial and lacustrine paludal sedimentary origin. These chocolate brown to grey sands generally weather to a characteristic mottled yellow colour. White angular quartz gravels are also locally prominent in the Walkerville South area. Recent stream alluvium (sand, silt etc.) has been deposited along the beds and margins of the deeply incised streams.

Altitudes vary from near sea level to just over 180 m at Mt. Liptrap (2.7 km inland). The local topography is an undulating surface with the slopes of broad crests attaining to 10° or more and leading down to deeply incised streams, up to 60 m below the crests. Perched depressions of various sizes are frequent on the crests, where there are also occasional small rocky outcrops. High cliffs (to 80 m) line the western shoreline at the Cape and this rocky coastline continues around the east towards Venus Bay.

Infertile soils with impeded drainage are common throughout the area. Here the soil profile shows a duplex light to dark grey clayey silt to 30 cm, over a yellow-mottled medium to heavy-textured clay to 1 m, the latter covering decom-

posed rock (Grant, K., in press). The restricted internal drainage of these soils means that they are frequently waterlogged to the surface during the wetter (winter) months. Under such anaerobic and strongly acidic conditions there is a substantial accumulation of undecomposed fibrous plant material in the surface horizons. In extreme situations an amorphous peat or mull develops, particularly where sphagnum moss is prevalent. Leaching, the predominant soil-forming process here, has led to a profile that is strongly acidic throughout and markedly deficient in plant nutrients, particularly phosphorus (Paton & Hosking 1970).

Deeper Tertiary sands occur as isolated rises throughout and as more extensive patches in the north of the area investigated. Here the depth of the surface horizon, somewhat darkened with organic matter, is more variable (< 1 m) and passes into a bleached subsurface horizon (to more than 2 m; Grant, *loc. cit.*). These soils are rarely if ever waterlogged, with the pH of the surface ranging between 4.8 and 5.7. Such deep infertile leached sands and badly drained peaty sands have been described as normal for heaths (Kirkpatrick 1975).

Occasionally the parent material outcrops at the surface and here the characteristically stony or gravelly shallow soils that develop are closely dependent on the nature of this parent rock e.g. the pH can be substantially raised where the outcropping rock is limestone.

Elsewhere deeper, humic soils typically less acid in reaction at the surface have developed over yellow-clay subsoils. Leaching may not be excessive and this may have led to a less deficient nutrient status, with drainage between the excessively draining and severely impeded soils described above. Combined with the moderate water-retaining capacity of these soils, this means that the vegetation growing here is unlikely to experience great fluctuations in available soil-water (Groves 1965).

DATA COLLECTION AND SYNTHESIS

Sampling Methods: Unlike other Zürich-Montpellier vegetation analyses e.g., Coetzee (1974) and Bridgewater (1976), all relevé sites were not selected individually in apparently homogeneous units. As the vegetation assessment formed part of a study attempting to determine the habitat utilization and preferences of small mammal species, relevés were located along trapping lines at regular intervals of 10 m. These trapping lines were selected so that the first two or three relevés were located in apparently homogeneous vegetation units. However, rarely were the final relevés of the line located in the same association as the initial ones.

As these relevés were a predetermined set distance apart (10 m) and all four corners were also predetermined, a relevé occasionally included a marked vegetation discontinuity and/or two apparently distinct communities. These samples were not discarded but were included in the final analysis and treated the same as other apparently homogeneous samples. This inclusion of samples containing marked vegetation discontinuities (so that *all* relevés sampled were included in the analysis) must reduce the criticism, frequently levelled at the Zürich-Montpellier system, that selection for vegetation homogeneity at the sampling site over-emphasizes the discontinuity between communities (Poore 1955a, Goodall 1961, Bouxin 1975).

Before selecting an appropriate relevé size minimal area curves were drawn up for four greatly differing community types (i.e. forest, mature 'dry' heath, recently-burnt 'wet' heath and severely wind-pruned heath). These curves all indicated as suitable the relevé size of 9-16 m^2 which has been found before in similar vegetation (Grant 1974, Gullan 1975). However releves of 100 m^2 (10 m x 10 m squares) were used to coincide with the intended trapping program.

Vegetation description was as outlined in Bridgewater (1971), with all vascular plant, bryophyte and larger lichen species, including epiphytes, recorded and assigned a value on the cover abundance scale of Braun-Blanquet (1964). 'Cover' was defined as the amount of ground space that would be covered by an irregular polygon tracing the outline of the plant. Species were not assigned a value on a sociability scale. Special note was made of any marked local biological or physical discontinuities (e.g. tracks, sphagnum patches, road drains). All data were recorded on cards providing a list of species likely to occur in the area. This greatly reduced the amount of time required to adequately assess the relevés.

The vegetation was sampled on various occasions between June and December with most relevés assessed only once. Unlike vegetation types where there is a strongly seasonal climate (e.g. the Mallee) and where time of year of sampling and recent weather conditions are of crucial importance in association determination (Holland 1971), few species were missed in this single sample. This is probably due to the uniform maritime climate.

Community Analysis: Although it is possible to synthesize meaningful vegetation associations

without the assistance of computers, as outlined by Bridgewater (1971), the amount and complexity of the data collected meant that a hand-sort of that type would have been so time-consuming as to be impracticable. Consequently, the initial complexity of the data was reduced by computer sorting using programs devised by Gullan (1975).

The data collected were coded onto cards with the ability to store information on up to 250 species. This meant that only those species that occurred very infrequently (generally in less than 4 relevés) were omitted from the analysis. The data were then analysed using the CARJAC/ ZUMONT (CANDE NAME = MAGIC) sorting program, a non-hierarchical, polythetic, agglomerative process based on the Carlson Cluster technique (Carlson 1972) using the Jaccard coefficient of similarity (see Gullan 1975). This initial sort so reduced the complexity of the data that the analysis was completed by hand-sorting using the printing program ZUMONT/ NEW (CANDE NAME = BUFF).

PLANT COMMUNITIES

Unlike previous Zürich-Montpellier studies the communities distinguished were not assigned names. Ideally, the determination and naming of a hierarchical classification, as outlined by Bridgewater (1971), should await a regional synthesis. Consequently the groups determined were referred to as Community One, Community Two etc. with a further descriptive name derived from the system of Specht (1972).

Community One — Closed Scrub (*Melaleuca ericifolia* dominant).

Easily distinguished structurally by the dominance of *Melaleuca ericifolia* as the sole caopy species at cover values of greater than 80%, this community's main differential species are *Ptychomnion aciculare, Festuca hookerana, Luzula meridionalis, Poa tenera, Ranunculus glabrifolius, Dichondra repens* and *Geranium solanderi*. Shrub species are very infrequent; only two are commonly recorded (*Acacia verticillata* and *Helichrysum dendroideum*).

This community, identifiable as the *Melaleuca ericifolia* thicket association of Parsons (1966) and Community Five (*Melaleuca ericifolia*) of Grant (1974), is restricted to a broad, flat, elevated drainage line between forested slopes. The humic soils, with significant clay content at depth and high water-table, probably result in little fluctuation in available water. This consistently high water-table may be the main factor in excluding both the *Eucalyptus* species of the adjoining forest and the species otherwise widespread throughout the other communities (i.e. *Drosera auriculata, Gonocarpus tetragynus* and *Epacris impressa*).

Community Two — Open Forest (*Eucalyptus obliqua* dominant).

The ubiquitous occurrence of *Eucalyptus obliqua* as the sole canopy species and *Tetrarrhena juncea* as a physiognomic dominant of the lower vegetation readily distinguishes this widespread community which is undoubtedly the predominant forest-type of the area. Although structurally very distinct, this vegetation type shares many species with Community One, principally a group of eight herbs (*Acaena anserinifolia, Cotula australis, Galium gaudichaudii, Geranium potentilloides, Hydrocotyle hirta, Hypericum gramineum, Lagenophora stipitata* and *Oxalis corniculata*), the mosses *Thuidium furfurosum* and *Hypnum cupressiforme*, and the lichen *Ramalina menziesii*. *Melaleuca ericifolia*, a canopy dominant of Community One (cover 80%), also occurs throughout Commmunity Two, but here as the major understorey component at cover values of not greater than 45%.

This community occurs only on the eastern slopes, where it is sheltered from the prevailing westerly winds, and on humic podsols of moderate fertility. Four species dominate to the extent of comprising by far the greater proportion of the photosynthetic biomass (ignoring woody parts) i.e. *Eucalyptus obliqua, Melaleuca ericifolia, Tetrarrhena juncea* and *Pteridium esculentum*. This may be due to a severe fire in 1971 as isolated individuals of more fire-sensitive species (e.g. *Coprosma quadrifida, Olearia lirata*) occur throughout this forest-type.

Community Three — Open Forest (*Eucalyptus radiata/E. obliqua* dominant).

The primary differential species of this forest-type are *Pultenaea daphnoides, Chaetophyllopus whiteleggei, Lepidosperma laterale, Lomandra filiformis* and *Acrotriche serrulata*. This community is structurally similar to Community Two but there are many significant floristic differences. *E. obliqua* and *E. radiata* occur as codominants and the major understorey species are *P. daphnoides, Leptospermum juniperinum* and *Acacia stricta*. *Tetrarrhena juncea* remains as an important, (though less so) component but the many small herbaceous hemicryptophytes so distinctive of the previous two communities are absent. Instead, the taller, more sclerophyllous *Lomandra filiformis*,

Diplarrena moraea and *Lepidosperma laterale* and the dwarf shrub *Acrotriche serrulata* typify the field layer.

This forest-type occurs on the more exposed rounded hill-tops. The soils are less humic and have a greater sand content and more variable moisture status than those of the preceding Community Two. Although structurally similar to Community Two this community is more closely related, floristically, to the following vegetation type.

COMMUNITY FOUR — LOW WOODLAND
(*Eucalyptus radiata* dominant).

Although falling within the definition of a Low Woodland this vegetation type could be more realistically described as a Closed Heath with an occasional emergent *E. radiata*. This community is somewhat transitional between Community Three and the following heath communities. A number of species is shared with the forest communities (e.g. *E. radiata, A. stricta, Galium gaudichaudii, Viola hederacea*) and there is a further group of more typically heathland species (e.g. *Selaginella uliginosa, Calorophus lateriflorus, Hypolaena fastigiata, Leptospermum myrsinoides*). However certain species which are otherwise widespread and common in heath communities are noticeably absent (e.g. *Cassytha* spp., *Casuarina* spp., *Dillwynia* spp., *Leptocarpus tenax, Xanthosia pusilla*). This community occurs as a single patch, less than 5 ha, isolated from other heath communities by an extensive area of Community Three. It is believed that this distinct local variant is a response to frequent fires from the adjoining road and farmland, and an infertile sandy soil in an area of otherwise moderately fertile humic loams over yellow clay.

COMMUNITY FIVE — CLOSED HEATH
(*Melaleuca squarrosa/Leptospermum juniperinum/ Casuarina paludosa* dominant).

The primary differential species for this association are the dominant *Melaleuca squarrosa*, and *Calorophus lateriflorus, Sprengelia incarnata, Boronia parviflora* and *Cassytha pubescens. Pultenaea stricta* is also frequent and restricted to this vegetation type but this may be a reponse to recent fires. The overriding impression of this vegetation type is an exceedingly dense closed heath (canopy coverage 95%), approximately 1 m tall and variously dominated by *M. squarrosa, C. paludosa* and/or *Leptospermum juniperinum. Leptocarpus tenax* frequently emerges to heights of 1.5 to 2 m. In a mature community, herbaceous species are rare and of low coverage. However, after a fire the species richness is very high, frequently up to 45 vascular species per 100 m^2 relevé.

This community occupies the largest area of extant native vegetation. It is analogous to Association C (Melaleuca-Selaginelletum of Grant (1974)), particularly the Sub-association C2-Casuarinetosum, and also shows some similarities to the *Melaleuca squarrosa* heath association of Parsons (1966) and to Group 6 of Gullan (1976), which is characterized by *Melaleuca squarrosa, Leptospermum juniperinum* and *Gahnia sieberana*.

The characteristic soils of Community Five are shallow, loamy sands overlying clays at about 30 cm depth with a compacted, drainage-impeding layer close to the surface. During the winter months a perched water-table develops and the whole A horizon becomes waterlogged. Locally there may be extended periods when there is free surface water. The nutrient status of these infertile soils, the soil/water relations and the growth of the vegetation is more fully discussed by Groves and Specht (1965).

A variant (or distinct association) occurs in small patches throughout this community. The differential species are *Sphagnum cymbifoliodes, Machaerina tetragona, Epacris microphylla, Villarsia exaltata* and *Xyris operculata*. The canopy of *Melaleuca squarrosa* and *Leptospermum juniperinum* is stunted and much more open than in the adjacent Community Five, and many of the low sclerophyllous 'heath' species are absent. The field layer is frequently a dense stand of a few species of sedges. The highly organic, acid soils (peats) are permanently waterlogged, with free surface water in winter as the slopes are negligible.

COMMUNITY SIX — CLOSED HEATH
(*Casuarina pusilla/Leptospermum myrsinoides* dominant).

Differential species for this distinct community are *Gompholobium huegelii, Leucopogon virgatus, Monotoca scoparia, Acacia suaveolens* and *Casuarina pusilla*. Although structurally very similar to Community Five, the dominant species are *Casuarina pusilla, Leptospermum myrsinoides* and *Banksia marginata; Leptospermum juniperinum* is also frequent. The zone of transition between Communities Five and Six is frequently no greater than 1 m wide, particularly in mature vegetation. This may be a direct response to a fluctuating water-table or an indirect response to changes in available nutrients, particularly phosphorus, as the water-table rises and falls (see Jones 1975).

This community occurs on isolated rises where deep Tertiary siliceous sands overlie the soils typical of Community Five. An almost identical community has been reported from other localities in Victoria with similar soils e.g. Cranbourne (Groups 1 and 2 of Gullan 1976), Westernport (the Leptospermo-Monotocetum association of Grant 1974) and Wilsons Promontory (Parsons 1966). The water-table does not approach the soil surface, as it does in the *Melaleuca squarrosa* dominated heathland, and the soils are much less organic.

COMMUNITY SEVEN — OPEN HEATH
(*Casuarina* spp./*Hakea sericea*/*Acacia myrtifolia* dominant).

Limestone outcrops at the northwestern end of one of the ridges and here there is a very shallow rocky soil of higher pH and nutrient status than is typical for the adjoining heathland. The vegetation type that has developed on these very exposed slopes is structurally and floristically distinct. Primary differential species are *Acacia myrtifolia, Drosera pygmaea, Hakea sericea* and *Sphaerolobium vimineum.* There are occasional very stunted shrubs of *Eucalyptus radiata.* Although the species generally restricted to Community Five are absent, *Casuarina paludosa* and *Lindsaya linearis* are frequent indicating that this is not a local variant of Community Six, but rather a distinct species association.

This community can be further divided into a variant of the shallowest soils of the most exposed locations, typified by a low species diversity and the presence of *Lepidosperma laterale, Diplarrena moraea* and *Xanthosia tridentata*, and a variant of deeper soils, where some of the species typical of Community Six may be found.

COMMUNITY EIGHT — CLOSED HEATH
(*Leptospermum laevigatum*/*Leptospermum juniperinum*/*Casuarina paludosa* dominant).

In this community the differential species include the dominant *Leptospermum laevigatum* and the most frequent understorey species *Machaerina juncea.* Further differential species are *Hibbertia sericea, Astroloma humifusum, Comesperma volubile* and the distinct variety *Acacia verticillata* var. *ovoidea.* This community is undoubtedly most closely related to Community Six but there is a number of important differences i.e. the absence of *Acacia suaveolens, Casuarina pusilla, Gompholobium huegelii* and *Monotoca scoparia*, important differential species of that community, and the consistent presence of *Casuarina paludosa, Acrotriche serrulata* and *Viola sieberana.*

This community is found only on the elevated headland of the Cape, but is widespread there. The surface has a relatively high pH (6 to 6.2) and is subject to considerable wind-borne salt input. However the profile soon increases in acidity (pH 4.8 to 5 at 20 mm depth) and then remains more or less constant throughout the leached, yellow sands of the A horizon (pH 5.2 at 39 cm). An impeding coffee-rock layer (organically cemented sand) may still form, although this is rarely close enough to the surface to induce anaerobic conditions approaching those of the soils of Community Five in winter. This strongly acid hardpan (pH 4.5) may be as close as 0.2 m to the surface or much deeper, to greater than 0.6 m.

On more protected slopes, often nearer the sea, where the soils are the deep calcareous dunes typical of coastal locations in many parts of Victoria, there is an abrupt transition to a Closed Scrub (*L. laevigatum* dominant) community. This is the *L. laevigatum* thicket of Parsons (1966) and the Leptospermo-Leucopogetum association of Grant (1974). The boundary is frequently marked by the hybrid *Banksia integrifolia* x *Banksia marginata.*

Communities 5, 6, 7 and 8 are not only structurally similar (all heathland) but have certain species in common as well. These species, indicating relationship at a higher hierarchical level, are *Banksia marginata, Cladia aggregata, Hypolaena fastigiata, Patersonia fragilis, Schoenus tenuissimus* and *Xanthosia pusilla.*

Similarly, communities 3 to 8 inclusive, share *Burchardia umbellata, Leptospermum juniperinum* and *Opercularia varia.*

The most generally distributed species occur more or less evenly and regularly throughout all communities except Community One, which is the most floristically and structurally distinct of the species assemblages. These widespread species are *Campylopus introflexus, Drosera auriculata, Epacris impressa* and *Gonocarpus tetragynus.*

A species group worthy of particular mention is found in the five species *Drosera peltata, Laxmannia gracilis, Marianthus procumbens, Platysace heterophylla* and *Tetrarrhena distichophylla.* These herbs are all of similar procumbent habit and occur throughout Community Seven and in those areas of Community Five that were recently burnt. This group appears to be a response to a particular structural situation (i.e. a more open canopy with greater light penetration throughout and a greater light intensity at ground level) in heathland areas of seasonally high water-

table. As these burnt areas mature these species will presumably decrease in importance. They are of only very sporadic occurrence in mature heaths of Community Five. Conversely, *Epacris obtusifolia* occurs solely in mature vegetation (of Community Five) where there is no evidence of a recent fire.

There are a few species which, although not infrequent, have distributions which do not conform to the community types distinguished and discussed above. For example, *Leucopogon australis* is not uncommon in Communities One, Three and Four and reappears consistently in *Sphagnum*-dominated areas of Community Five. There is a relatively high light intensity at ground level and consistently and reliably high soil moisture in these locations. Elsewhere either the light intensity at ground level is lower or the soil moisture is more variable. *Cladonia* spp. (at least two — *C. pityrea* and *C. verticillata* — and possibly more) occur sporadically throughout the area, but consistently in locations that have not experienced a fire for some time.

DISCUSSION

These plant communities comprehensively account for all the non-coastal vegetation of the uncleared land in the Cape Liptrap-Walkerville area. The major community determinants appear to be the nutrient status of the soil, fluctuations in the depth of the water-table and the presence of an impeding layer close to the surface.

It is important to note that the Zürich-Montpellier Association Analysis takes account of the complete species complement of the vegetation and not just the dominants or uppermost stratum species. Although physiognomically dominant species were often also differential species for particular communities, the recognition of communities by dominant species would have led to a different result. For example, *Eucalyptus kitsoniana* and *Eucalyptus viminalis* var. *racemosa* were occasionally emergent above stands of Community Five. Yet no other floristic differences were apparent between those relevés with and those without these trees; consequently there is no basis for distinguishing two more communities solely on the presence or absence of these two species. Similarly, consideration of the species of the uppermost stratum only would have ignored the frequently precise community change between Community Five and the *Sphagnum*-dominated variant.

Consideration of the total species complement may further help in determining community relationships. Although Communities One and Two are very different structurally and in their dominants, the large number of species shared in common implies greater similarity and a much closer relationship between these two communities than there at first appears. Conversely, Communities Two and Three, although in the same structural category (Open Forest), have few species in common and are not closely related floristically.

The regional relationships of the flora are difficult to determine as the author is aware of few Zurich-Montpellier studies, apart from those of Grant (1974) and Gullan (1975), in comparable vegetation. However, certain of the communities distinguished are recognizable in vegetation studies using other techniques. Community Six, Closed Heath (*Casuarina pusilla/Leptospermum myrsinoides* dominant), is apparently widespread in southern Victoria, as other workers have reported a more or less identical association in similar soils e.g. at Cranbourne (Gullan 1975), Westernport (Grant 1974), Wilsons Promontory (Groves and Specht 1965, Parsons 1966). Furthermore this may be the same vegetation type reported from Corner Inlet (Turner *et al.* 1962), Cheltenham (Patton 1933) and from extensive sandplains at Keith in South Australia (Specht & Rayson 1957), although in these localities the vegetation is less compatibly defined.

Similarly, Community One, Closed Scrub (*Melaleuca ericifolia* dominant) reappears at Westernport and Wilsons Promontory. Structurally similar vegetation with the same canopy dominant is frequent in poorly drained situations in southern Victoria but as the floristics are rarely adequately discussed its identity with Community One is doubtful.

Community Five, Close Heath (*Melaleuca squarrosa/Leptospermum juniperinum/Casuarina paludosa* dominant), may be identical with both the heath association of exposed locations reported from East Gippsland (L.C.C. 1974) and Association C (Melaleuca-Selaginelletum, subassociation C.I) of Grant (1974) at Westernport. A similar possibly identical, community has also been described from Cape Otway by Parsons, Kirkpatrick and Carr (1977). In other areas where *M. squarrosa* dominates the floristics, structure and edaphic conditions indicate a distinctly different association.

Associations similar to Communities 7 and 8, Open Heath (*Casuarina* spp./*Hakea sericea*/*Acacia myrtifolia* dominant) and Closed Heath (*Leptospermum laevigatum/Leptospermum juniperinum/Casuarina paludosa* dominant) respectively, have not been reported elsewhere.

These two vegetation types are probably a response to a unique set of local conditions and may be restricted to the Walkerville area.

The distribution of the vegetation types represented by Communities Two and Three, Open Forest (*Eucalyptus obliqua* dominant) and Open Forest (*Eucalyptus radiata*/*Eucalyptus obliqua* dominant) respectively, is unknown (these associations have not been recorded elsewhere). Carolan (1976) records both the dominant species (*E. obliqua* and *E. radiata*) in near-coastal situations on the eastern coast of the Southern Otways and *E. obliqua* at Port Campbell. As climatic and edaphic conditions appear similar to Walkerville these associations may re-occur at the above locations, and elsewhere in western Victoria. *E. obliqua* apparently does not reach the coast east of Wilsons Promontory.

Climatically and edaphically, as well as floristically, the relationships of the Walkerville vegetation appear to lie more with that of southwestern Victoria than with East Gippsland, especially in view of the southwestern or south-central affinities of many of the dominant or characteristic species (e.g. southwestern — *Machaerina acuta, Casuarina pusilla, Isopogon ceratophyllus, Pultenaea stricta;* south-central — *Acacia verticillata* var. *ovoidea, Eucalyptus kitsoniana, Hibbertia procumbens*). With the exception of *Melaleuca ericifolia*, those species with pronounced eastern affinites are rare and sporadic in occurrence e.g. *Banksia serrata, Hakea teretifolia, Sowerbaea juncea, Xanthosia pilosa*, and are neither dominant nor characteristic of the communities. However to further understand the regional relationships of the vegetation much more work is needed, particularly in southwestern Victoria, from the Lower Glenelg River to the eastern Otways.

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TABLE 1

CONSTANCY OF THE MORE COMMON SPECIES IN COMMUNITIES

I — 0 to 9% II — 10 to 19%, etc. to X — 90 to 100%

Community number	1	2	3	4	5	6	7	8
No. vascular plant spp. per 100 sq. m. relevé mean (± s.d.)	26.9 (±3.5)	21.1 (±4.1)	30.6 (±4.3)	36.7 (±3.2)	35.1 (±4.2)	36.2 (±4.8)	43.7 (±5.2)	37.3 (±5.6)
Ptychomnion aciculare	X	II						
Festuca hookerana	VIII							
Luzula meridionalis[1]	X	II	III					
Poa tenera	X	IV						
Ranunculus glabrifolius	X	I						
Dichondra repens	X	III						
Geranium solanderi	IX		III					
Helichrysum dendroideum	VII		II					
Acacia verticillata	X	VIII						
Melaleuca ericifolia	X	X	III					
Acaena anserinifolia	X	IV						
Cotula australis	X	V						
Galium gaudichaudii	X	VIII	II	V				
Geranium potentilloides	X	VII						
Hydrocotyle hirta	X	X	III					
Hypericum gramineum	VI	VII	III					
Lagenophora stipitata	X	X	VIII					
Oxalis corniculata	X	VI						
Thuidium furfurosum	VIII	VI						
Hypnum cupressiforme	X	VII						
Ramalina menziesii	IX	VIII						
Coprosoma quadrifida	X	VIII						
Deyeuxia quadriseta		VIII						
Lophocolea semiteres	II	X	II	III				
Eucalyptus obliqua		X	X					
Tetrarrhena juncea		X	X					
Pultenaea daphnoides		II	IX					
Chaetophyllopus whiteleggei			VIII					
Lepidosperma laterale	II		IX				V	
Lomandra filiformis		I	X		VIII	IX	X	III
Acrotriche serrulata		II	X		II	II	VI	X
Eucalyptus radiata		II	X	X				
Acacia stricta		II	IX	X				
Dianella revoluta		I	III	IX				
Xanthorrhoea minor				X	IV	I	V	

Except where otherwise indicated, (see Table and below) all vascular plant nomenclature follows Churchill and de Corona 1972. 1. pro parte *Luzula campestris*. 2. syn. *Haloragis tetragyna*. 3. sp. nov. Orchard, 1975; pro parte *Haloragis teucrioides*. 4. sp. nov. Vickery 1970; pro parte *Poa australis*.

Full tables and a comprehensive list of all plant species collected are available from the author on request. A near-comprehensive herbarium has been collected and is lodged in the Departmental Herbarium, Botany Department, Monash University.

TABLE 1

CONSTANCY OF THE MORE COMMON SPECIES IN COMMUNITIES

I — 0 to 9%   II — 10 to 19%, etc. to   X — 90 to 100%

Community number	1	2	3	4	5	6	7	8
Melaleuca squarrosa				X	X	II		
Calorophus lateriflorus				VI	X	III	I	
Sprengelia incarnata					VIII			
Boronia parviflora					VIII			
Cassytha pubescens					VI			
Pultenaea stricta					VI	III		
Leptocarpus tenax					IX	VI		II
Gompholobium huegelii					IV	VII	III	
Leucopogon virgatus						VIII	VI	IX
Monotoca scoparia					III	VIII	VI	
Acacia suaveolens					III	X	VII	IV
Casuarina pusilla					II	X	VIII	
Acacia myrtifolia						II	X	I
Drosera pygmaea					II	II	VIII	
Hakea sericea							VIII	
Sphaerolobium vimineum						I	X	III
Diplarrena moraea			VI				VIII	
Xanthosia tridentata						I	VIII	IV
Leptospermum laevigatum								X
Machaerina juncea								X
Hibbertia sericea								X
Astroloma humifusum						III		VIII
Comesperma volubile								VI
Acacia verticillata var. ovoidea					II	II	III	VIII
Isopogon ceratophyllus						III	III	X
Lepidosperma concavum					II	X	X	X
Viola sieberana					II	I	IX	IX
Cassytha glabella					IX	IX	X	V
Casuarina paludosa					X	IV	IX	X
Dillwynia glaberrima					IX	X	VII	
Dilwynia sericea					IV	VIII	X	V
Goebelobryum sp.					VI	V	IV	
Helichrysum scorpioides					VI	VIII	VI	III
Laxmannia gracilis					V	V	X	II
Lethocolea spp.					VII	V	VI	I
Lindsaya linearis					X	V	IX	
Patersonia fragilis					IX	X	VI	IX
Pimelea humilis					IV	IX	X	X
Platylobium obtusangulum					V	X	IX	V
Xanthosia pusilla					X	X	X	IX

TABLE 1

CONSTANCY OF THE MORE COMMON SPECIES IN COMMUNITIES

I — 0 to 9%   II — 10 to 19%, etc. to   X — 90 to 100%

Community number	1	2	3	4	5	6	7	8
Amperea xiphoclada				X	VII	X	VI	VII
Banksia marginata				III	X	X	X	X
Hypolaena fastigiata				VI	IX	X	VI	X
Leptospermum myrsinoides				VIII	VII	X	IX	X
Platysace heterophylla				X	V	IV	VI	
Schoenus tenuissimus				X	X	IX	VIII	VIII
Selaginella uliginosa				VI	X	VII	V	
Bryum billardieri	IX	IV	V	II	II			
Billardiera scandens	II	III	VI	X	II			
*Hypochoeris radicata	IX	V	X	VI				
Parmelia spp.	VIII	III	III					
Usnea spp.	I	VIII	III					
Viola hederacea	IX	X	X	VI				
Burchardia umbellata		I	V	X	X	IX	X	X
Cladia aggregata		II	VIII	VI	IX	X	VI	X
Epacris impressa		V	X	X	X	X	X	X
Leptospermum juniperinum		I	X	X	X	X	X	X
Lomandra longifolia		II	III	X	V	IV	IV	VII
Opercularia varia		II	IX	X	IX	VII	X	VII
Campylopus introflexus	II	VIII	X	X	X	X	X	X
Cladonia spp.	VI	IV	VI	II	IX	IX	IV	X
Drosera auriculata	II	VIII	X	X	VI	VIII	X	VII
Gonocarpus tetragynus[2]		X	X	X	X	X	X	X
Pteridium esculentum	V	X	X	X	I	V	II	III
Aotus ericoides						III	III	I
Bauera rubioides			VI	V	III			
Dampiera stricta					V			
Danthonia semiannularis		V	VIII					
Drosera peltata					IV	IV		
Drosera whittakeri					VII	IV		
Exocarpos strictus	VI	I		III				
Gnaphalium japonicum	VI	I	VIII	II				
Gonocarpus humilus[3]	II	V						
Hibbertia acicularis					I	IV		III
Leucopogon australis	VI		VIII	IX	IIII			
Machaerina acuta						II	VI	
Marianthus procumbens					VI	IV	VII	
Mitrasacme pilosa var. stuartii				X	VI	IV	VIII	
Platylobium formosum			II	V				
Poa sieberana[4]		III						
Xanthosia dissecta					III			

ROYAL SOCIETY OF VICTORIA

1977

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ABRIDGED REPORT OF THE COUNCIL

FOR THE YEAR ENDING 10 MARCH, 1977

MEETINGS AND LECTURES

During the year, ten Ordinary Meetings were held.

MARCH 11—After the Annual General Meeting, Dr. R. G. Ward spoke on "The Development of the Flying Machine".

APRIL 8—"The Ruling of Microscopically Fine Diffraction Gratings — an account of Australian contributions since 1910". Mr. J. J. McNeill. Members were invited to visit the Division of Chemical Physics, CSIRO, on 7th May and to inspect equipment referred to in that lecture.

MAY 6—"Progress towards a Flora and a Biological Survey of Australia". Dr. W. D. L. Ride.

JUNE 10—"Microsurgery". Mr. J. A. Snell. By kind permission of the Board of Governors, this Meeting was held at the Alfred Hospital.

JULY 8—"Galapagos and Hawaii — a biological comparison". Professor I. W. B. Thornton.

AUGUST 12—"Theories of Angiosperm Evolution". Professor W. D. Tidwell.

SEPTEMBER 9—"The Next Million Years". Sir Macfarlane Burnet.

OCTOBER 14—"The Role of Deakin University". Dr. F. R. Jevons.

NOVEMBER 11—Soiree. The Society's Research Medal for 1975 was presented to Professor Ronald Taft, who then delivered his Medal Lecture, "The Study of Immigrant Adjustment — is it science or common sense?".
Exhibits were provided by CSIRO Division of Applied Geomechanics, ICI Australia Limited, the Mines Department, the National Museum and the School of Geology, University of Melbourne.

DECEMBER 2—"Information from Mars". Professor J. F. Lovering.

MEMBERSHIP *at 1st January 1977:*

Honorary Life Members 4, Life Members 45, Members 534, Associates 58. Total 641.

Council recorded with regret the deaths of Lord Casey (Honorary Life Member), Mr. H. C. C. Langdon and Mr. N. V. Salter.

PROCEEDINGS

During the year the Society published Volume 88 (Parts 1 and 2 in one cover) at a net cost of $6576, after receipt by the printer of Book Bounty amounting to $2059.

Council acknowledges with gratitude an increased grant from the Victorian Government and grants from the Australian National University and Mr. E. D. Gill towards the costs of publication.

LIBRARY

2054 volumes and parts were received during the year mainly from exchanges with 62 Australian and 267 overseas organizations. Members contributed $188 towards the cost of binding and 51 volumes were bound at a cost of $378. 501 items were borrowed from the Library (546 in 1975). About 50 sets of photo-copies of library material were supplied.

HALL

In addition to the Society and the Royal College of Obstetricians and Gynaecologists, 27 professional and other bodies held 119 meetings on the premises compared with 113 meetings by 22 bodies in 1975.

Extensive plumbing repairs ($580) and repairs to roof gutter ($319) were carried out.

SUBMISSIONS

The Society has made submissions to the Industries Assistance Commission inquiry into the Publishing Industry, the Interim Australian Science and Technology Council, and to the Independent Inquiry into the CSIRO.

CONGRATULATIONS

Council congratulates Professor A. B. Wardrop on his election to Fellowship of the Australian Academy of Science.

FINANCE

The year's operations showed a surplus of $4847, mainly on account of the relatively low cost of publishing Volume 88 of "Proceedings". Means of reducing publishing costs have been discussed with the printers. It has been necessary to make a further increase in Members' subscriptions, to $18 per annum.

The Society's financial position remains sound, but heavy expenditure on publications will be incurred early in the year. Increases in subscriptions and rents have kept pace with increasing costs of operation, but by inflation, capital holdings have lost value.

The Hall and Cottage are valued, as assets, at the 1955 figure of $85,500 and are insured at a replacement value estimated in 1973 at $234,000.

ACKNOWLEDGEMENTS

Council, on behalf of the Society, expresses its thanks to the many persons and organizations who have given valuable assistance during the year, including Mr. H. G. Stevens, Honorary Auditor; Mr. D. Clarebrough on behalf of Sir Ian Potter, Honorary Financial Adviser; Mr. Leigh Masel, Honorary Solicitor; Mr. F. Suendermann and Mr. N. Strahan on behalf of Sir Roy Grounds, Honorary Architect; ICI Australia Limited; The Parks, Gardens and Recreation Department of the Melbourne City Council and Mrs. I. Sadik.

J. F. LOVERING
President.

INDEX TO VOLUME 90

INDEX

INSTRUCTIONS TO AUTHORS

Detailed lists of these Instructions are available from the Executive Officer. The following is an abbreviated version only.

Papers considered for publication may be Reviews, Reports of experimental or descriptive research, or Short Communications. Length of Papers may vary; Short Communications should not be longer than 1,500 words.

Two copies of the manuscript, with any accompanying Plates and Figures, should be submitted initially to the Executive Officer at the Society's Hall, 9 Victoria Street, Melbourne, 3000.

Manuscripts must be typed on quarto paper, double-spaced, on one side of paper only, and with ample margins. Captions to Text Figures and Explanations of Plates must be attached to the Ms as final pages. Underlining should be restricted to generic and specific names of biological taxa. Measurements must be expressed in the metric system (SI units).

References should be listed alphabetically at the end of the paper. Abbreviations of titles of periodicals must conform with those in *A World List of Scientific Periodicals* (1963-4, 4th ed., London, Butterworth). References to books should give the year of publication, number of edition, city of publication, name of publisher. Titles of books and (abbreviated) names of periodicals should be underlined, in the typed list of references.

Maximum size for **Plates** is 15·5 cm x 21 cm. Photographs must have clear definition and may be submitted as either glossy or flat prints, at actual size for reproduction. Each Plate (photograph) must be mounted on white card to furnish a white surround of at least 5 cm, and the Plate number clearly labelled on back of card.

Line drawing for **Text Figures** should be made in black ink on white card or drawing linen. Maximum size (full page) is 15·5 cm x 21·0 cm: single column width 7·5 cm. Figures are preferably submitted *at actual size*: they may well be drawn larger and photographed by the author to be submitted as glossy prints of required size. Graphic scales must be included with the drawings, and on maps and geographical plan views, compass directions should be indicated. Lettering on Figures must be inserted by the author, and special care is needed to ensure that all letters and numerals are still readable when the Figure is reduced.

Oversized illustrations, tables or maps are accepted for publication as **Foldouts** only with the understanding that the author meet any additional costs involved in their production. Maximum size for Foldouts is 21 cm x 31·5 cm.

Short **Tables** will be type-set within the text. Extensive Tables which are likely to cover one page of print should be typed, on an electric typewriter to ensure clarity and evenness, within the dimensions 27·9 cm x 22·5 cm. They should then be photographed to reduce them to full page size, 15·5 cm x 21 cm, and submitted as glossy prints. They will be reproduced on metal, not type-set, and hence must be finally correct when submitted, since they cannot be corrected at the proof stage.

The Society supplies authors with 25 **Reprints** free of charge; joint authors receive a total of 30. Additional reprints may be ordered by returning the order blank which accompanies the galley proofs.

SYMPOSIA

Papers presented at Regional and other Symposia organized by the Royal Society of Victoria have been printed in its *Proceedings* and are available as follows:

THE VICTORIAN HIGH PLAINS. Included in Vol. 75, Part 2, 1962. $6.25 per copy.

THE BASALT PLAINS OF WESTERN VICTORIA. Included in Vol. 77, Part 2, 1964. $6.25 per copy.

THE VICTORIAN MALLEE. Included in Vol. 79, Part 2, 1966. $6.25 per copy.

EAST GIPPSLAND SYMPOSIUM. Vol. 82, Part 1, 1969. $5.00 per copy.

THE AQUATIC ENVIRONMENT AND MAN. Included in Vol. 83, Part 1, 1969. $5.00 per copy.

WEST GIPPSLAND SYMPOSIUM. Reprinted from Vol. 84, Part 1, 1969. 80 cents per copy.

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THE RIVER MURRAY – A VIEW FROM SPACE

Man's conquest of space has generated a spin-off of many technological benefits in industry and everyday life.

One of the most important and widely useful is imagery of the Earth obtained by special satellites positioned in precise orbits for the specific purpose of recording Earth phenomena.

Uses of the information gathered are extensive. They include the compiling of inventories of urban development, assessment of flood damage and measuring the extent of bushfires. Analyses for the prediction of world-wide wheat crop yields are being undertaken. The extent of pollution in rivers, the sea and the air is monitored. Photographic reproductions covering the world are available, showing geology, forests, beaches, water resources, snow fields, deserts, mountain ranges and cities.

This project sheet is designed to show how the Victorian Water Commission makes use of Earth Satellite Imagery as a tool in the assessment of different aspects of the States water resources. In this case the image is of the River Murray from Albury to Mildura.

For further information on the activities of the Water Commission, write to The Public Relations Officer, Victorian Water Commission, 590 Orrong Road, Armadale, Victoria, 3143, or ring (Melbourne) 508 0247.

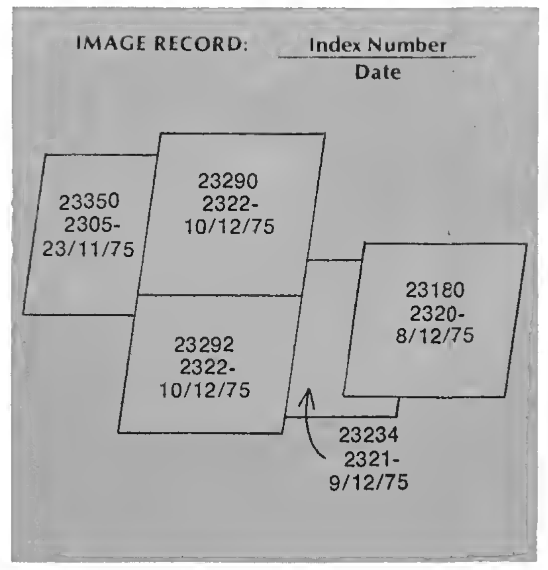
VICTORIAN WATER COMMISSION PROJECT SHEET NO. 3

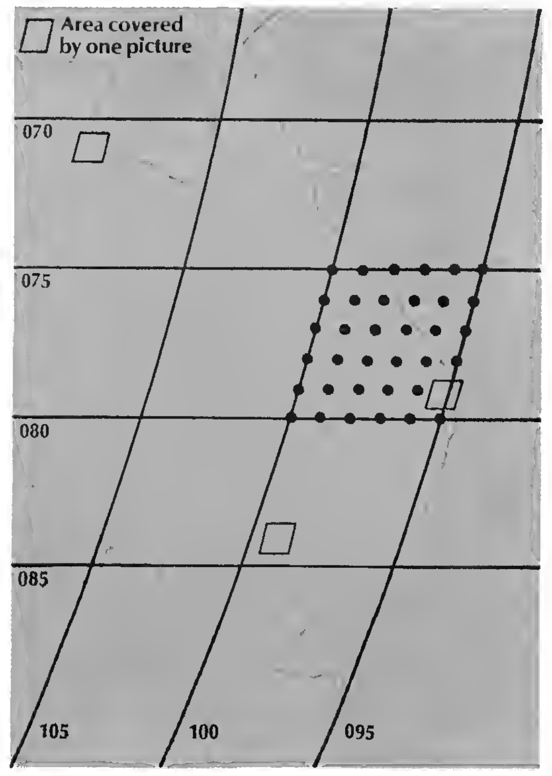
The Satellite System

The Landsat 1 satellite was launched by the North American Space Administration (NASA) in July, 1972, to record the features on the earth's surface. It was the first of a planned series of 4 which will enable the same area to be viewed every 3 days. The second satellite was launched early in 1975, the third will be launched in September, 1977, and the fourth in 1981.

The satellites circle the earth from the north to the south at a height of 920 km, taking 102 minutes to complete one orbit. They are synchronized with the speed of the sun so that each pass, say over Australia, will be between 9 a.m. and 10 a.m., resulting in the pass over Victoria coinciding with the same time as its next pass 102 minutes later over Western Australia. On each pass a strip of land 185 km wide is photographed by one system while another system senses the various light wave lengths. The information is stored on tape and relayed back to receiving stations in the United States of America, Canada, South America, Europe, Africa and Australia (1979).

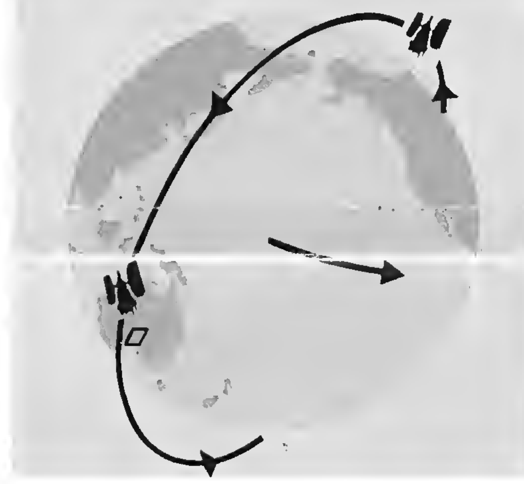
The first system used photographic materials and records four visible wave length bands of the spectrum. The other system, a scanning device, senses the different bands instead of photographing them. It also senses a band of reflected infra red wave lengths which are beyond the range of visible light. The third satellite will include a device which will sense temperature differences on the earth's surface.





It takes 500 or so Landsat images to totally cover Australia. The images are individually identified by three-digit path and row numbers. Thus the image including Brisbane, as shown on our map, is 095-079.

The smallest unit of definition available in Landsat imagery is known as a pixel, short for picture-element. It measures just 80 metres square.



Landsat orbits from pole to pole while the Earth rotates beneath it. In 18 days it can photograph (or sense) conditions over the complete surface of the Earth.

What Landsat Looks Like in Orbit

The River Murray System

The colour reproduction is of the River Murray system from Albury to Mildura. The area shown was recorded by the Landsat 2 satellite between 23rd November, 1975, and 10th December, 1975. These scenes are repeats of an earlier series taken by NASA to show the time it takes for floods to pass along the River Murray. At the time these images were recorded the floods had reached Mildura, after passing Albury one month earlier.

The State Rivers and Water Supply Commission obtained the images from NASA, when NASA activated the satellite over the flooded areas in response to a request from the Science Attache, Australian Embassy, Washington, D.C. The request was forwarded to the Australian Embassy by the Department of National Mapping, Canberra, on behalf of the State Rivers and Water Supply Commission, Victoria.

Colours

False colours have been used to obtain a greater contrast between the colours reflected by the land surface features. The red colour has been substituted for the green of living vegetation. The red colour represents the amount of the infra red light wave lengths which are reflected from the leaves of plants and trees, and this contrasts with the water. The water is reproduced as a black colour because it does not reflect any of the infra red wave lengths. However, when the water is muddy, it will reflect the infra red wave lengths, the reflectance is due to the sediment in the water, and it is shown as a blue colour. Shallow lakes with salt deposits on the lake bed will show either as a blue colour when covered with water, or white when the deposits are exposed.

There are different intensities of the red colour, the lighter reds indicate the irrigated crops, from Cobram to Swan Hill, and around both Robinvale and Mildura, which are on the River Murray. Irrigated crops can be identified between the Goulburn, Campaspe and Loddon Rivers, from the same colours. The dark reds identify the mountain forests, these are south of Albury, and also the reed beds along the Edward and Murrumbidgee Rivers which are in New South Wales.

The dull brown colour depicts the Mallee scrub and eucalypts in the drier climatic zones. The green patchwork areas are ploughed ground or bare soil and the yellow identifies the areas of dry crops of wheat, or dry natural vegetation, such as grass.

River Course Features

The differences in the width of the River Murray are due to natural interruptions along its course. It has taken thousands of years to form its present course and in that time it has had to erode through, or by-pass, a number of barriers across its path.

The wide flood plain below Albury persists as far as the Barmah-Millewa Forest. It then spreads out as a fan between Echuca and Deniliquin. The change from a constricted flood plain to a fan formation was caused by a fault which thrust a block of land up out of the plain and disrupted the river course some 20,000 years ago. It was forced to flow around the north end of the tilted area past Deniliquin. Eight thousand years ago the Murray changed its course at the same barrier and flowed south across a number of lake floors in front of the tilted block to take over the Goulburn River flood plain near Echuca.

Downstream of Echuca the River Murray effluents break out of the smaller flood plain which had been established by the Goulburn River. The numerous breakaways travel north west through the Koondrook Forest towards its old flood plain in the north. The river narrows as it enters the Mallee at Swan Hill and opens out again when it enters its former flood plain.

The Barmah-Millewa forest, a river forest of red gum, has become established on the alluvial fan because it is flooded seasonally. Similarly, the Koondrook Forest is maintained by seasonal river overflows between Cohuna and Kerang.

Reservoirs and Lakes

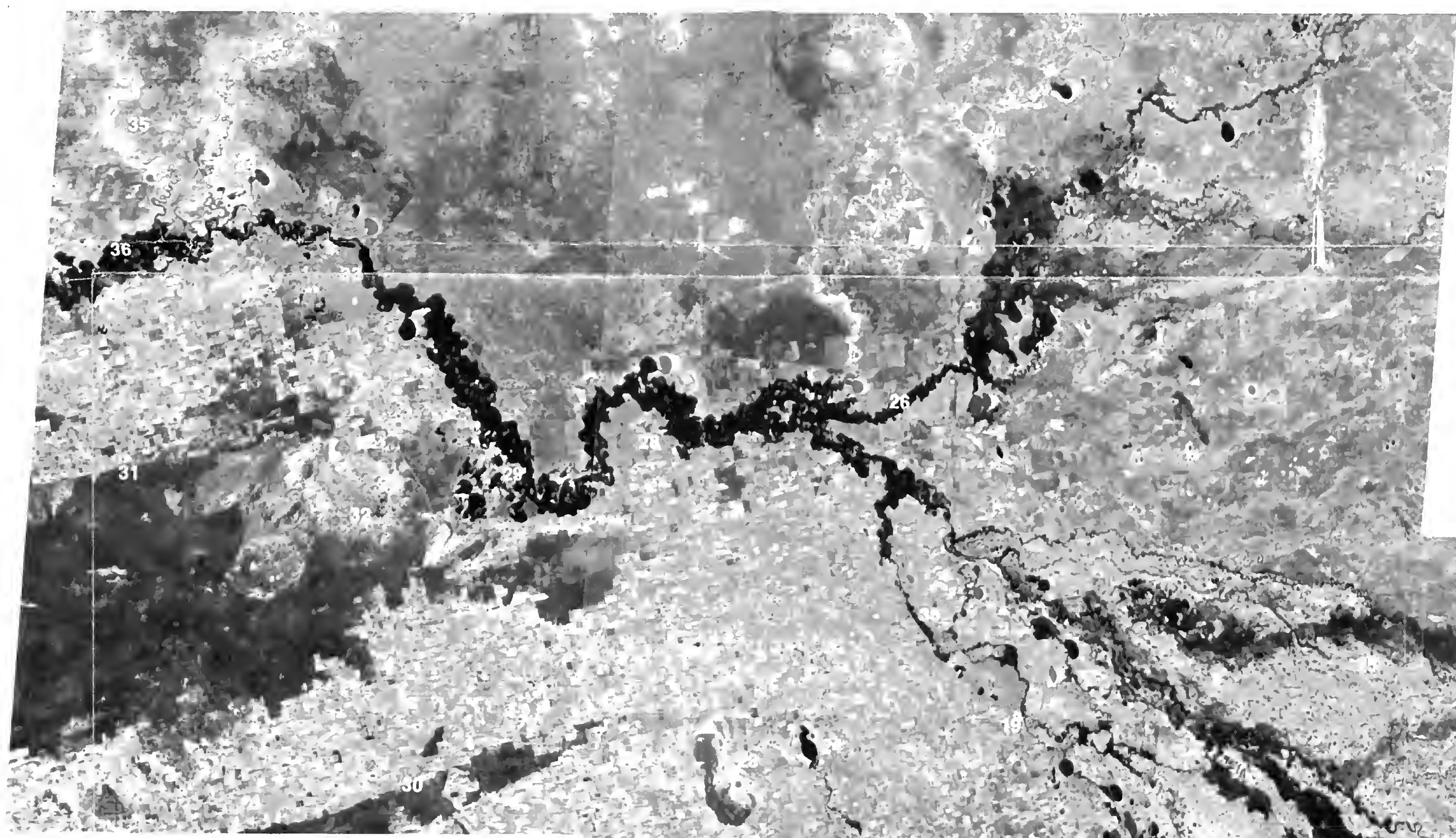
The reservoirs and lake systems show as black or blue areas. On the River Murray the Hume Reservoir is upstream from Albury and the Yarrawonga Weir downstream. The Ovens River flows into the Murray at the tail water of Lake Mulwala (Yarrawonga Weir). Lake Mokoan, an off-river storage to the South of Yarrawonga — receives its water from the Broken River, and Waranga, another off-river storage, is fed from the Goulburn River. Near Waranga are the Corop Lakes which were formed on the downthrown side of the same fault which caused the diversion of the River Murray past Deniliquin. North of these lakes is the remnant of Lake Kanyapella, which is used as an irrigation drainage basin. Further north are the Moira and Barmah Lakes, which straddle the River Murray, in the Barmah Forest. Kow Swamp, another off-river storage, supplies the Torrumbarry Irrigation system. Water is diverted into the swamp from the Torrumbarry Weir, which is constructed across the River Murray. Sediment in suspension gives it its blue appearance and the dark patch on the eastern side shows the point of entry of the diverted water.

Further west, the Bael Bael terminal lakes of the Avoca River show a variety of colours. Bael Bael receives sediment from the Avoca and to the east a white rimmed salt lake is showing blue from bottom reflection of the salt deposits. Lake Buloke to the south west has swelled enormously due to the years of high rainfall. Lake tyrrell to the north is in the Mallee among the wheat farms. Salt is mined from its floor. Lake Tyrrell is the terminal lake of the Tyrrell Creek and Lake Timboram to the east is the terminal lake of the Lalbert Creek.

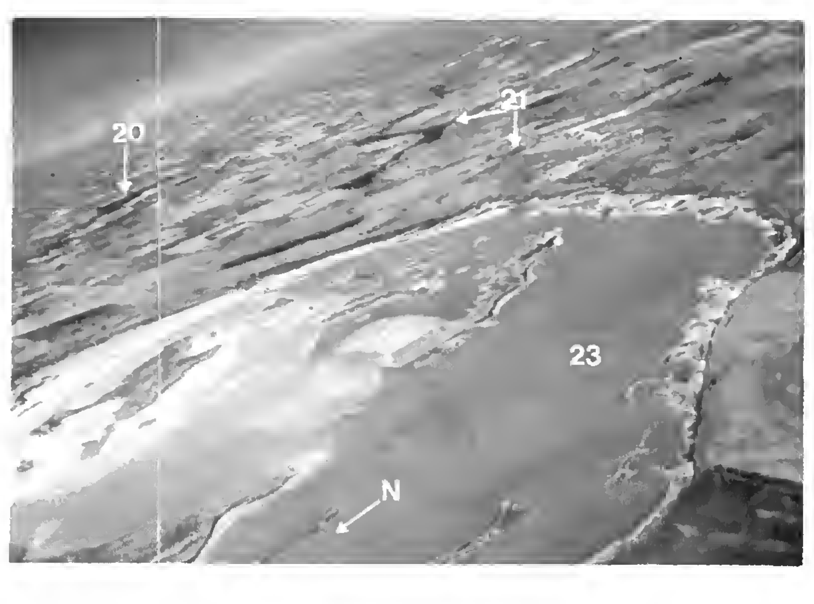
To the north the flooded River Murray is joined by the Wakool River. Further north the reed swamps straddling the Murrumbidgee River show as a red colour, although the area is flooded. This indicates that the reeds protrude above the flood water which has also spilled over and inundated all of the small lakes in the area. The position of the lakes can be determined by the crescent shaped sand dunes (lunettes), which also rise out of the flood water. The dunes are formed around the lakes eastern margin by the wind. The large dry lake bed to the north west is bounded by high sand hills and named "The Walls of China". These too are lunettes and nearby the "Mungo Man" was found; human remains 28,000 years old.

Features near Mildura

The river narrows past Mildura and is flanked by vineyards and orchards, showing an orange colour. Similarly there are small irrigated plots on the river bank upstream as far as Robinvale. To the south is the Mallee scrub of the Sunset country and the tip of the Big Desert vegetation. The gypsum deposits of the Raak Plain show as a green circular patch in the Sunset country and to the east are the flooded Hattah Lakes in the Bend of the River Murray which then turns north. Downstream from Mildura the Darling River joins the Murray, as does the Great Ana Branch immediately to the west. The Darling supports sparse patches of river gum along its course, depicted by the red colour, and this contrasts with the lack of trees along the course of the Ana Branch.




Oblique aerial photograph, in natural colour, of the southern part of Lake Tyrrell (23) which is fed by Tyrrell Creek (21). Lalbert Creek (20) flows into Lake Timboram.



Key To Locations Numbered

1 Lake Hume, 2 Albury, 3 Lake Mulwala (Yarrawonga Weir), 4 Lake Mokoan, 5 Ovens River, 6 Goulburn River, 7 Waranga Reservoir, 8 Corop Lakes, 9 Barmah-Millewa Forest, 10 Deniliquin, 11 Echuca 12 Lake Kanyapella, 13 Kow Swamp, 14 Torrumbarry Weir, 15 Loddon River, 16 Campaspe River, 17 Avoca River, 18 Bael Bael Lakes, 19 Swan Hill, 20 Lalbert Creek, 21 Tyrrell Creek, 22 Lake Buloke, 23 Lake Tyrrell, 24 Lake Timboram, 25 Wakool, 26 Murrumbidgee River, 27 Walls of China (part), 28 Robinvale, 29 Hattah Lakes, 30 Big Desert, 31 Sunset Country, 32 Raak Plains, 33 Mildura, 34 Darling River, 35 Big Ana Branch, 36 River Murray.

COLOUR KEY:

RED — vegetation (reeds and mountain forests); ORANGE — irrigation; BROWN — eucalypts; YELLOW — dry vegetation; GREEN — bare ground (desert, ploughed fields); BLACK — water; BLUE — water with sediment; WHITE — salt.

Compiled by D. T. Currey, Supervising Geologist, State Rivers and Water Supply Commission.